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INVESTIGATING COORDINATION IN MULTIDEGREE OF FREEDOM CONTROL I: TIME-ON-TARGET ANALYSIS OF 6 DOF TRACKING

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In these two companion papers, methods developed in a series of studies in the 1940’s and 1950’s are applied to the analysis of 6 DOF control devices used in modern human machine systems such as teleoperation and virtual environments. Contrary to the early studies, the current work showed that the simultaneous time-on-target in multidegree of freedom tracking was higher than the product of component time on target scores. The distribution of linear correlation coefficients between the tracking errors of different degrees of freedom tended to be skewed towards the positive values. These results suggested that subjects’ discoordination in early multidegree of freedom tracking studies was likely due to the limitation of human machine interfaces at that time. With well designed interfaces, subjects exhibited more coordinated trials than discoordinated trials in multidegree of freedom tracking.

INTRODUCTION

It has always been interesting to read about early efforts in the exploration of a new science. The late 1940's and early 1950's was a time of intense interest in human control of systems. This interest was driven in part by developments in Control Theory and Information Theory and in part by the demands of the sponsoring agencies, chiefly military. Behavioral theorists saw in the emerging engineering approaches new ways of formalizing human behavior. The sponsors' concern was largely one of whether a target would be hit. Ease of computation and high face validity led to the use of "time-on-target" as a measure of "tracking" performance. It was natural that the study of multiple degree-of-freedom (DOF) tasks would arise (e.g. Ellson, 1947; Senders, Christensen, & Sabeh, 1955; Senders, Wallis, & Senders, 1956). Poor performance in multiple DOF control was attributed to lack of "coordination". It was not clear whether "coordination" was a purely human characteristic or arose from interaction with equipment design.

The growing number of applications of teleoperation, virtual environments and other 3D human machine systems has renewed research interest in coordination. Manual controllers have been designed to allow translational and rotational manipulation in 3D space with 6 DOF (see Brooks & Bejczy, 1985; Jacobus, Riggs, Jacobus, & Weinstein, 1992, and Zhai, 1995 for reviews). How well human operators can handle all 6 DOF has not been satisfactorily resolved especially with respect to control with one hand. Rice, Yorchak and Hartley (1986) 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 (1987) contradicted Rice’s observation, however, and found no differences between two 3 DOF controllers and one 6 DOF controller. To base the design and selection of multidegree of freedom control interfaces on a firm ground, human coordination in using 6 DOF control devices is a fundamental problem that must be addressed.

A quantitative (and preferably analytic) measure of coordination that also satisfies intuitive understanding of the concept is of critical importance. Ellson (1947) derived independence measures of percent time-on-target scores (TOT) on the DOFs (azimuth, elevation, and range) of the Pedestal Sight Manipulation Test (PSMT). He recorded *simultaneous* TOT's (STOT) in all pairs of dimensions as well as all three at once, in addition to TOT's 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 (uncorrelated). If greater, they were positively correlated; if less, negatively correlated. Ellson found that the tracking of most subjects was characterized by a slightly negative relationship: STOT scores were slightly less than the products of the component TOT scores. In other words, there was some tendency for the subjects to be off target in one dimension when on target in another dimension. Gardner found that when subjects used a joystick control with a cross-pointer display (Gardner, 1950) the function $\mathrm{STOT} - (\mathrm{TOT}_X)\cdot(\mathrm{TOT})_y$ was not significantly different from zero.

Senders (Senders et al., 1956) extended Ellson's approach. He placed the scores on a two DOF task into a 2 x 2 matrix of STOT and component TOT's and computed the phi-coefficient, Ø. Ø is an approximation of the product-moment correlation coefficient of two arbitrarily dichotomized continuous variables. Senders and colleagues found that subjects’ tracking in a two DOF task which required manipulation of two knobs to control a pointer on a dial, produced more negatively correlated than positively correlated trials and, with continued practice, actually produced larger negative correlations.

If one operator could not coordinate tracking in two axes, it might be better to assign the tracking task to two operators. Such an issue was studied in (Senders et al., 1955) which had three groups of subjects participating in a two dimensional tracking task. Members in Group I tracked both dimensions. The second group had several *teams of two* subjects performing the tracking task; each subject operated one dimension of the task and information about both dimensions was displayed to the team. The third group worked the same way as in Group II but each subject of the team was presented with only the dimension that he was tracking. Results showed that Group I performed at a much lower level of performance than the teamed groups (as measured by component TOT's as well as STOT’s).

These early studies seemed to suggest a rather pessimistic view of one operator’s ability to coordinate two or more dimensions. Note, however, that the negative correlations between dimensions were not necessarily due to subjects’ inability to coordinate control actions, but possibly an artifact of the control and display interfaces available at the time. In Ellson's study, the PSMT did not permit "the correction of simultaneous errors in several dimensions by a single well-coordinated movement." (Ellson, 1947). In Senders' study, the displays were separated and each control was operated by one hand. In Gardner's study (Gardner, 1950), although a joystick and a cross pointer display were used, "opportunity did not exist for a single corrective movement for errors in both dimensions". Whether operators could coordinate multiple DOF control, if appropriate interfaces were provided, remains an open question. We have turned a PC into a virtual time machine and gone back to do what could not reasonably have been done then.

Modern interfaces in teleoperation and 3D display systems, although involving even more DOFs than the traditional two or three dimensional interfaces, are better integrated. The rest of this paper presents an application (though mediated by a modern computer) of the thinking and analysis developed more than 40 years ago to data produced in a 6 DOF tracking task with integrated control and display.

THE EXPERIMENT

Experimental Task

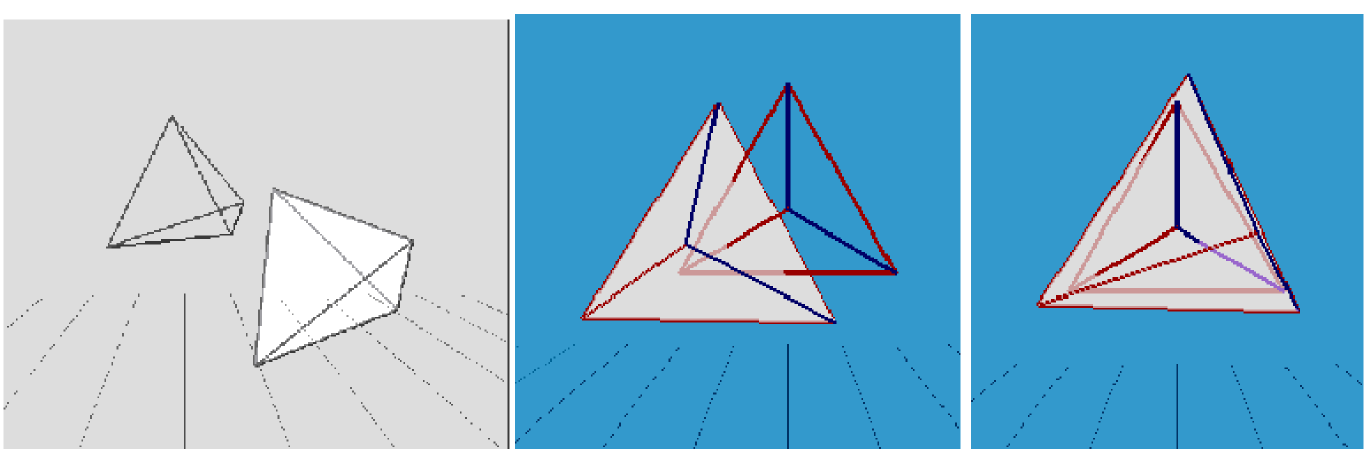
The task involved pursuit tracking in 6 DOF. Subjects controlled a 3D cursor to align it as closely as possible in both position and angular orientation with a 3D target that moved unpredictably (Figure 1). Both the target and the cursor were tetrahedrons. To ensure that only one possible correct orientation match existed each tetrahedron had two blue adjacent edges; the remaining edges were colored red.

The cursor and the target had two differences to help minimize potential confusion: 1) the radius (center to any vertex) of the cursor was 1.3 times that of the target; 2) the cursor had semi-transparent surfaces while the target was a "wireframe" model.

The target motion was driven by six independent forcing functions with identical frequency characteristics, one for each DOF. These were weighted combinations of 20 sine functions with a random initial phase, such as:

$$x(t) = \sum_{i=0}^{19} A\, p^{-i} \sin(2\pi f_0 p^i t + \phi_x(i)) \qquad (1)$$

where t is the time duration from the beginning of each experimental test and the constants A = 3.5, p = 1.25, f_o = 0.01. These values were set through pilot testing so that the target remained within the bounds of the display and moved at a challenging but manageable speed. $\Phi_x(i)$ (i = 0,..., 20) were independent pseudo-random numbers between 0 and 2π.



(a) (b) (c)

Figure 1. *6 DOF tracking task. The tetrahedron with semi-transparent surfaces is the cursor. The tetrahedron without semi-transparent surfaces is the randomly moving target. Subjects tried to align the cursor with the target. Shown in the figure are examples of (a) a very large 6 DOF error between cursor and target (b) a large translation error and small rotation error, and (c) a small translation error and large rotation error.*

Experimental Apparatus

Display. In designing the 3D displays used in the experiment, four types of depth cues were chosen: binocular (stereoscopic) disparity, linear perspective, interposition (edge occlusion), and partial occlusion through semi-transparency. Binocular disparity, linear perspective and interposition are conventionally recognized as strong depth cues (Kaufman, 1974). The use of semi-transparency to create partial occlusion, as shown in Figure 1, is a novel technique, but has been shown to be both effective and easy to implement (Zhai, Buxton, & Milgram, 1996). During the experiment, subjects sat 60 cm away from the display and wore appropriate stereoscopic glasses. The experimental room was darkened throughout the experiment.

Input Controllers. Two 6 DOF input controllers were used in the experiment: a Spaceball™ and an Elastic General-purpose Grip controller (EGG), an egg shaped 6 DOF device designed by the first author (Figure 2). The Spaceball™ is an isometric, force sensitive device and the EGG is a suspended elastic resistance device whose displacement is proportional to the force and torque applied by the user. Both devices were operated in rate control mode.

Subjects. Thirty paid volunteers were screened. Three subjects were rejected for having weak stereoscopic acuity, and one was rejected for having poor corrected near-vision acuity. The accepted 26 subjects' ages ranged from 18 to 37. None of them had had prior experience with any 6 DOF manipulation devices. Thirteen subjects were assigned to the isometric rate controller (Spaceball™) and the remaining subjects to the EGG.

Procedure. Data gathering occurred over five phases. Each phase consisted of a practice session (3 minutes for Phase 1 and 7 minutes for the rest of the phases), followed by 4 trials of tracking. Each trial lasted 40 seconds. The entire experiment, including screening tests, lasted one hour for each subject.

TIME-ON-TARGET (TOT) BASED COORDINATION ANALYSIS

Method

A computer program, TOTscope, was developed to analyze TOT based coordination performance. TOT's in each of the 6 degrees of freedom were first calculated. The translational TOT's parameters were easy to compute. TOTx was defined as the total sum of time periods in which the translational distance between the target and the cursor in X dimension was smaller than a given threshold, divided by the total trial time (40 seconds). TOTy and TOTz were similarly defined.

TOTrx, TOTry, TOTrz, the time on target in rotational degrees of freedom required more careful definition. We used the X, Y, Z components of the rotation vector (See

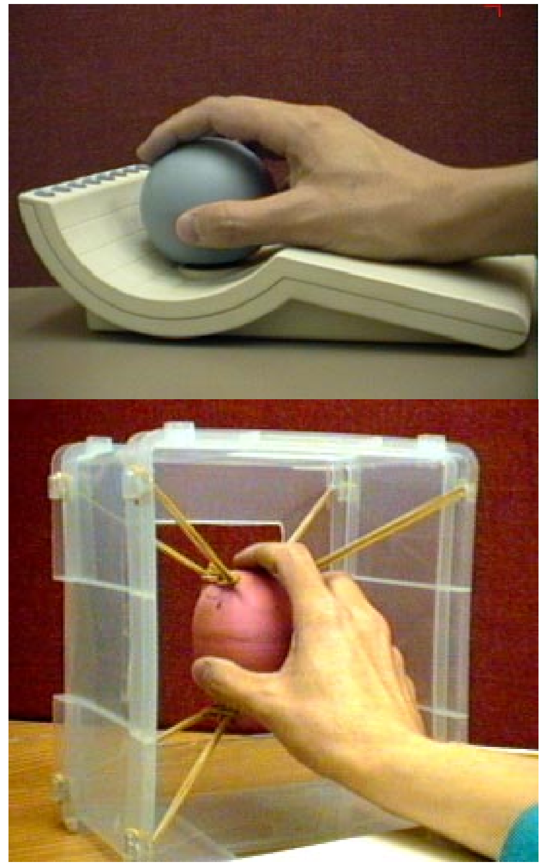


Figure 2*. The isometric Spaceball™ (top) and elastic EGG (bottom) input controllers used in the experiment*

Altmann, 1986) between the target and the cursor as the basis for calculating TOTrx, TOTry and TOTrz. TOTrx was defined as the total sum of time periods in which the X component of the rotation vector between the target and the cursor was smaller than a given threshold, divided by the total trial time (40 seconds). TOTry and TOTrz were similarly calculated.

Three higher order parameters, TOTb and TOTmin and STOT were then calculated. TOTb was the baseline target-on-target value, i.e. the probability purely by chance for all 6 degrees of freedom to be on target at the same time (Senders, 1956):

$$TOTb = TOTx \; TOTy \; TOTz \; TOTrx \; TOTry \; TOTrz \qquad (2)$$

TOTmin is simply the smallest of TOTx, TOTy, TOTz, TOTrx, TOTry, TOTrz, i.e.,

$$TOTmin = \min (TOTx, TOTy, TOTz, TOTrx, TOTry, TOTrz) \qquad (3)$$

STOT is the actual percentage of time-on-target simultaneously in all 6 DOF. The final parameter that TOTscope seeks is coefficient C:

$$C = (STOT - TOTb)/(TOTmin - TOTb) \quad (4)$$

C was intended to reflect the quality of coordination. For 0 < C < 1, TOTb < STOT < TOTmin, the trial is COORDINATED to the degree C indicates.(When C = 1, i.e. STOT = TOTmin, it is PERFECT coordination.) For C = 0, STOT = TOTb, it is no better than chance (UNCOORDINATED). For C < 0, STOT < TOTb, it is worse than chance (DISCOORDINATED).

Results

Figure 3 shows the TOT measures when 10, 20, 30 and 40 degrees of mismatch were chosen as the "on target" criterion. The thresholds for translational degrees of freedom were equivalent to the rotational threshold (i.e. rotational threshold multiplied by the cursor radius). Note that each data point on the graph is the mean of 26 subjects, each of whom performed 4 trials in each experimental phase.

Upon inspecting the graphs, the following observations can be made:

1. Although not perfect, subjects' 6 DOF tracking trials are coordinated as measured by the C ratio for all four thresholds. For the 10 degree threshold, C was about 0.15 and for all other thresholds, C was approximately 0.2. Remember that C could range from -1, discoordinated, to 0, uncoordinated, to 1, (perfectly) coordinated.

2. TOTmin, STOT and TOTb all improved in later experimental phases but the C value remained almost constant. This was contrary to our expectation of seeing an increase of the C value, as subjects gained more experience.

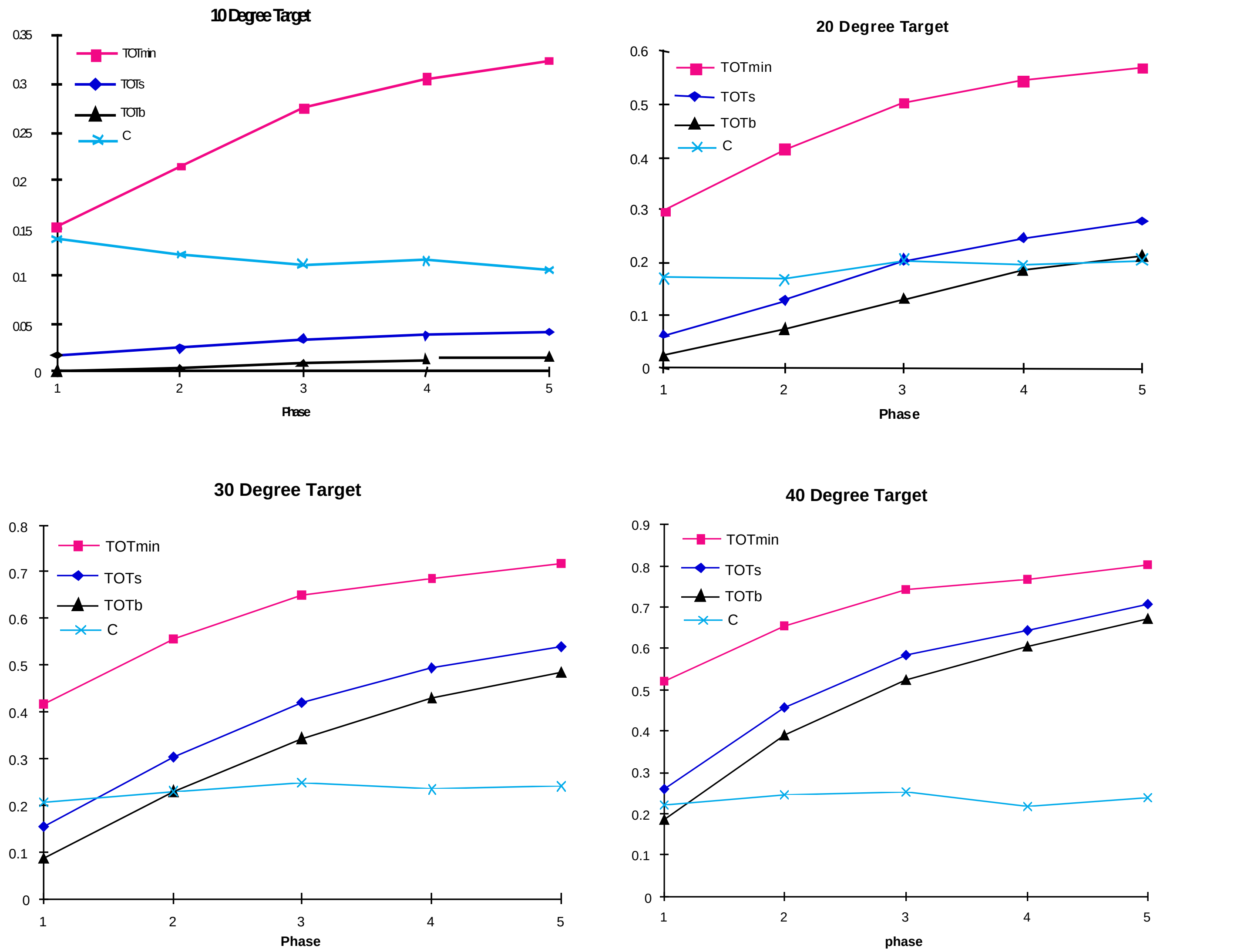


***Figure 3**. TOT measures under 10º , 20º , 30º and 40º time on target criteria*

CONCLUSION / TRANSITION

The modern data are at variance with those found by Ellson in a 3 DOF task. Using a TOT based coordination measure, we found that even 6 degrees of freedom can be. It is our contention that the differences arose in part because of the differences in the design of the control and display spaces. In particular, the modern controller permits to a much higher degree than the PSMT non-interacting control outputs by the human controller using one hand. Both Ellson's and Senders' subjects used two hands in control and it may be that discoordination arise there as well. In the next part of this work we examine the linear correlations of the data.

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