TELEOPERATOR TRACKING PERFORMANCE

IN SIX DEGREES OF FREEDOM

by

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ABSTRACT

This thesis discusses the results of experiments that focused on the abilities of human operators to perform tracking tasks in six degrees of freedom (dof) with one hand. The software used to create the simulated tracking environment was developed by the Man/Machine Systems Laboratory and the experimental hardware included an IRIS workstation display and a single six dof hand controller developed by the German Aerospace Research Establishment (DLR).

In space, tracking in six dof becomes an important issue. When using a display to track an object in space, certain degrees of freedom (dof) may provide the human operator with a better view and produce less error than other dof. The first set of experiments addressed these questions. Six MIT graduate students tracked a target ball with a cursor ball controlled with one hand through a single six dof hand controller. Tracking was done each of the six dof individually and a corresponding root mean square error (rmse) term for each dof was calculated as the measure of performance. The six dof were tested separately by having a single dof enabled and the other five dof turned off during each experimental run. These experiments showed that movement in the directions of x-translation and y-translation ("good" dof) produce less rmse than the other four dof: z-translation, z-rotation, x-rotation, and y-rotation ("bad dof").

In the second series of experiments, four MIT graduate students were used as test subjects and movement was varied in three dof combined instead of only one dof at a time. The two "good" dof were combined with each of the four "bad" dof individually for four experimental conditions. The software calculated an rmse as a performance measure for each of the three active dof in each experimental run.

In the final experimental run subjects tracked the target in all six dof at once, with an rmse calculated for each dof.

Some vehicles, such as spacecraft, move with an acceleration plant, because an input to a thruster causes the vehicle to continue moving indefinitely until another opposite thruster is fired. Manipulator arms have velocity gains because they work with gear trains that dictate an absolute change in position and a step input will not force the manipulator to move indefinitely. Due to the acceleration gains of space vehicles and the velocity gains of manipulators, all of the above tracking experiments were performed with both velocity inputs and acceleration inputs.

Before each set of experiments the subjects were trained to minimize effects of learning on the experimental data. The experimental design randomized the ordering of the experimental conditions. An analysis of variance was performed to statistically analyze the data.

The results revealed that z-translation produced significantly more rmse than the other translational dof. All of the rotational dof had rmse's that were statistically similar to each other. Acceleration control input yielded greater rmse than velocity input. There were also several significant interactions between dof and control plant where acceleration control increased rmse significantly more for certain dof than others. Conclusions and recommendations are made based on the experimental results. This thesis work is an extension of the author's masters thesis, "Effects of Force and Visual Feedback on Space Teleoperation; with Policy Implications" which was completed at MIT, in the Department of Mechanical Engineering, in June 1988.

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CHAPTER 1 - INTRODUCTION

Many operations that involve the use of remote manipulators require that human operators track various targets on display screens. For example, if it was desired to control an orbital maneuvering vehicle from a space station that would dock with a satellite such as a space telescope, the operator would have to track and dock with the target. This operation could be difficult given that the target could be moving randomly in six degrees of freedom.

This experimental study investigated human tracking performance in six degrees of freedom (dof). The tasks in these experiments were pursuit tracking tasks, where the subject saw both the object that he/she was controlling and the target object that he/she was tracking. In contrast, compensatory tracking provides the subject with a display of his/her error, i.e. the difference between the actual system response and the desired system response (Sheridan, 1974). Thus, with pursuit tracking the subject had a more visual model of performance (Poulton, 1967).

Previous studies on tracking investigated tracking in three dof (Poulton, 1974). However in space, tracking in six dof becomes important. When using a display to track an object in space, certain degrees of freedom may be in better view and the operator could track with less error than other dof. The first series of experiments addressed these questions. Subjects tracked a target ball with a controlled ball in each of the six degrees of freedom individually. The control ball was controlled with one hand through a single six dof hand controller. Corresponding root mean square errors for each dof were calculated quantifying performance while examining one dof at a time. In the next series of experiments, subjects tracked movement in combinations of three degrees of freedom at once. A rmse was calculated for each dof to determine how various combinations of degrees of freedom affected operator performance. The final series of experiments consisted of tracking in all six dof at once with an rmse calculated for each dof.

Space vehicles, such as the orbital maneuvering vehicle (OMV) move at constant velocity with a thruster step input adding acceleration and changing velocity. This can be viewed as an acceleration control plant or acceleration input by the operator to the system. When a thruster is given an input the vehicle will continue moving indefinitely until another opposite thruster is fired due to the frictionless space environment. Manipulator arms that work on gear trains will move differently in space than vehicles. This can be viewed as having a velocity control plant or a velocity input from the operator to the system. A step input from a controller to a manipulator will result in a change of position that will not move indefinitely due to the gear train moving the manipulator by a specific amount. The experiments were conducted with both acceleration and velocity inputs to simulate human tracking that might occur when controlling vehicles or manipulators in space.

CHAPTER 2 - EQUIPMENT

2.1 COMPUTER HARDWARE

The computer hardware used to conduct the tracking experiments included a Silicon Graphics Computer Systems IRIS 2400 Turbo Computer with an IRIS Graphics Display.

2.2 HAND CONTROLLER

A six degree of freedom, force/torque sensing, sensor ball hand controller built by the German Space Agency DLR was used as the input device for the tracking experiments. The DLR sensor ball can receive three force, or translational, commands and three torque, or rotational, commands and generate corresponding output. Its internal measuring system generates a new set of output data every four milliseconds independent of the rate of requests for data. Each request for data to the ball is acknowledged immediately to keep the response time as low as possible. (German Aerospace Research Establishment, 1987). Figure 2.1 shows the layout of the computer hardware and hand controller.

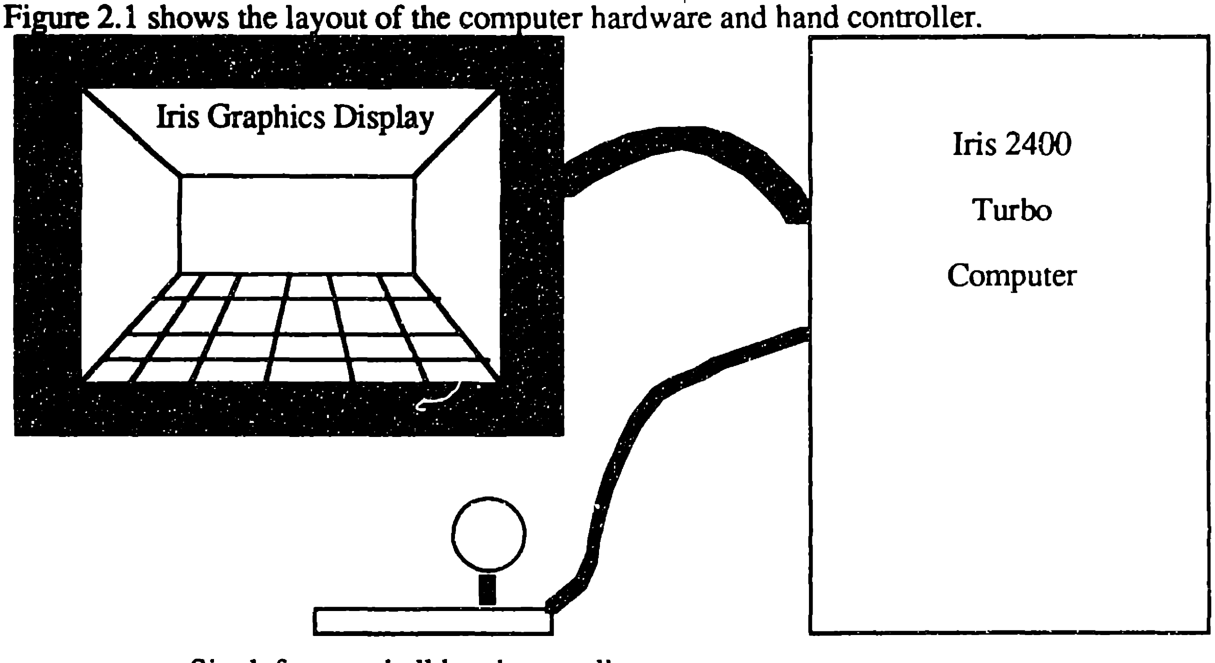

Figure 2.1 - Hardware Layout

2.3 SOFTWARE

The software that was used to simulate the tracking environment was written by Dr. James Roseborough, a former graduate student in the Man/Machine Systems Laboratory. Deirdre Hall, an MIT undergraduate student, customized the software enabling the desired testing to be performed.

The software was written on the IRIS using the UNIX operating system. The software enabled the test subjects to track the target ball that moved independently in a random manner with a ball that was controlled by the subject. The controlled ball was exactly the same shape and dimensions as the target ball. The subject controlled the controlled ball with the six dof hand controller. The target ball would move randomly on the display and was located inside of what appeared to the operator as a room. The room had plain white walls, a plain white ceiling, and a white floor with a grid of black lines. The subject was able to determine the relative position of target ball to controlled ball by the differences in the position of cross hairs on the target ball and the controlled ball and the difference in relative size between the two balls. Figure 2.2 gives a representation of the subjects' view. When the cursor was in front of the target in appeared larger than the target. When the cursor was too far behind the target, it would disappear. The room had linear perspective to providing apparent movement in three dimensions. The cutoff frequency of the target movement was .025 Hz. providing a slow target movement.

The controlled ball was controlled by input from the six dof hand controller that was interpreted as either velocity input or acceleration input. If the input was interpreted as velocity input, a change in force from the operator's hand to the hand controller would result in proportional velocity. The harder the subject would push on the controller, the faster the controlled ball would move. If the hand controller was centered with no force acting on it, the controlled ball would not move. If the input was set to acceleration mode, a force exerted on the hand controller would result in an acceleration of the controlled ball.

If the hand controller was centered with no force acting on it, the controlled ball would move at a constant velocity.

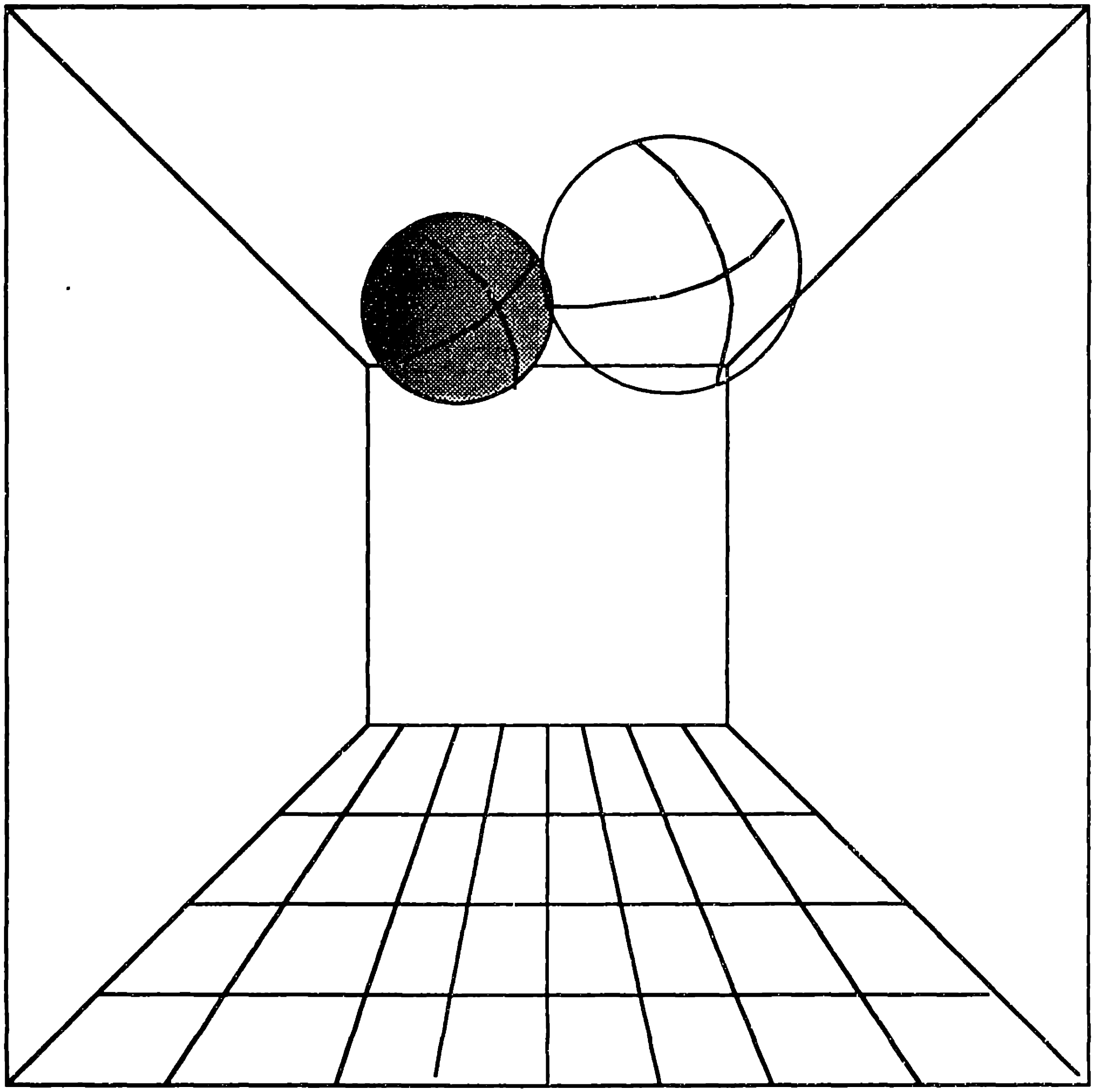

Figure 2.2 - Subjects' View of Experiments

Initial software parameters were input at the start of an experimental session, thereby controlling the number of degrees of freedom in which the target and controlled balls could move. Movement could occur in all six degrees of freedom: x-translation, y-translation, z-translation, x-rotation, y-rotation, and z-rotation. This movement could occur in only one dof during a trial or in any combination of the six dof.

The program recalculated the relative positions of the target and controlled ball at a sampling rate, or frame rate, of 10 Hz. At each sampling instance, a root mean square error (rmse) was calculated for each of the degrees of freedom that were operating. This error reflected the deviation in a particular dof between the position/orientation of the target ball (desired position) and the position of the controlled ball.

CHAPTER 3 - EXPERIMENTAL DESIGN

3.1 TASKS

The pursuit tracking task used in the experiments consisted of the operator trying to track the target ball that moved randomly according to the software parameters with the controlled ball that was controlled by the test subject through the six dof hand controller.

Since both the target and the controlled balls had cross hairs, the subjects tried to keep these sets of cross hairs lined up keeping the two balls at the same orientation and minimizing rotational tracking error. The subjects also tried to keep the controlled ball at the same location as the target on the display in order to minimize tracking error in the translational degrees of freedom. When the target and controlled balls were in front or behind each other, the error was displayed to the subject as a relative size difference. When the controlled ball was in front of the target ball it appeared larger than the target ball, when the controlled ball was directly behind the target ball it would disappear.

A standard coordinate system was used in the experiments consisting of combinations of translational movement along the horizontal or x-axis, the vertical or y-axis, and the axis coming out of and into the display or the z-axis. These axes are shown in relation to the display and to the hand controller in figure 3.1. Rotations about each one of the axes was also possible, with x-rotation simulating a pitch movement, y-rotation simulating yaw, and z-rotation simulating roll. These six degrees of freedom were tested individually and in various combinations.

The tasks were all performed both with acceleration and velocity inputs. This was done to determine the differences between tracking with each of those inputs, thus having relation to the control of space vehicles and manipulators.

The subjects used in the experiments were all male MIT graduate students between 22 and 26 years of age.

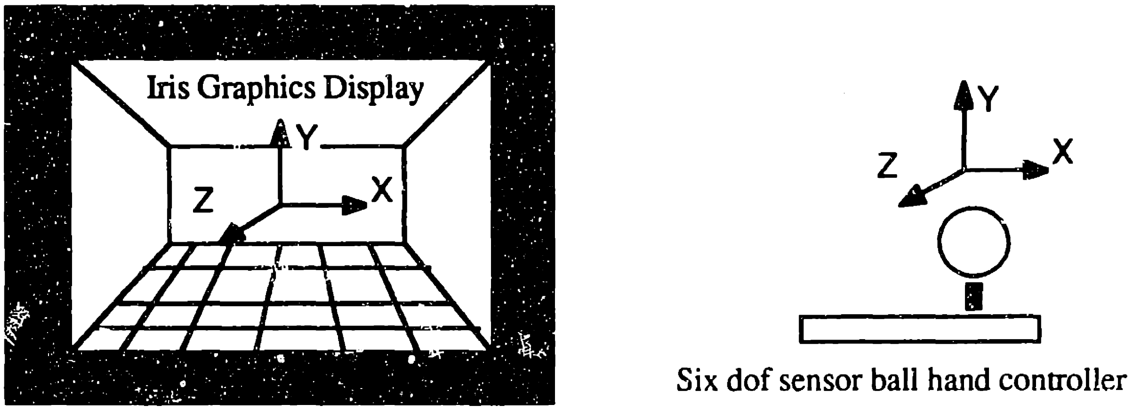

Figure 3.1 - Axes for Degrees of Freedom

3.2 TRACKING IN ONE DEGREE OF FREEDOM

When using a display to track an object in space, certain degrees of freedom (dof) may be in better view for the human operator and produce less error than other dof. In the first series of experiments six test subjects tracked the target ball in each of the six degrees of freedom, one degree of freedom at a time. Each dof was tested by having a single dof enabled and the other five dof disabled during an experimental run. The target ball moved in only one dof and the controlled ball would respond to input in that same dof only. A corresponding rmse for the dof being tested was calculated during each experimental run.

A within subjects experimental design was used, i.e. each subject performed every experimental condition and each subject acted as his own control. Each of the six dof were tested with the subjects controlling both an acceleration plant and a velocity plant for a total of twelve experimental conditions. These twelve experimental conditions were divided into two sessions. In one session the subject would track in each dof with an acceleration input, in the other session the subject would track in each dof with a velocity input. The six subjects were randomly given subject numbers. Subjects #1-3 tracked in each dof in the first session with the velocity input and in the second session with an acceleration input. Subjects #4-6 tracked in each dof individually with an acceleration input in the first session and with a velocity input in the second session.

A balanced latin square technique was used to counterbalance for the effects of learning and fatigue (Chapanis, 1959). The balanced latin square had each experimental condition precede and follow every other experimental condition an equal number of times. Therefore every dof that was tested preceded and followed every other dof an equal number of times for both acceleration and velocity control over all the experimental runs for all of the test subjects. The balanced latin square provided the ordering of dof to be tested for each subject as shown below in Table 3.1 (trans=translation, rot=rotation).

Trial #	Subj.#1	Subj.#2	Subj.#3	Subj.#4	Subj.#5	Subj#6
1	x-trans.	y-trans.	z-trans.	x-rot.	y-rot.	z-rot.
2	y-trans.	z-trans.	x-rot.	y-rot.	z-rot.	x-trans
3	z-rot.	x-trans.	y-trans.	z-trans.	x-rot.	y-rot.
4	z-trans.	x-rot.	y-rot.	z-rot.	x-trans	y-trans
5	y-rot.	z-rot.	x-trans	y-trans	z-trans.	x-rot.
6	x-rot.	y-rot.	z-rot.	x-trans.	y-trans.	z-trans.

Table 3.1 - Balanced Latin Square for Tracking in One Degree of Freedom

Each subject attended a one to two hour training session to become familiar with the equipment and experimental procedures. During the training sessions the subjects tracked the target ball with the controlled ball in each degree of freedom four times: two 2-minute trials with acceleration input and two 2-minute trials with velocity input for each dof. This helped to counterbalance the major effects of learning that would otherwise be present during the actual experimental sessions.

Then the subjects came back on separate days to perform the tracking tasks with acceleration input in one experimental session, and with velocity input in another experimental session. The order of the dof that each subject would track was shown previously. For each dof the subject would first track the target for a thirty second practice trial in order to adjust to the dof that he would be tracking in for subsequent trials. The practice trial was then followed by two data trials that lasted for three minutes each. The dof used for the data trials was the same dof used during the practice trial. Only the data from the data trials were used in the analysis. After the second data trial for a particular dof, the subject would then proceed to the next dof performing the practice trial and the two data trials for that dof. Figure 3.2 shows the test matrix for these experiments.

degree of freedom / control plant	x-trans.	y-trans.	z-trans.	x-rot.	y-rot.	z-rot
Acceleration	x-trans, accel.	y-trans, accel.	z-trans, accel	x-rot, accel	y-rot, accel	z-rot, accel
Velocity	x-trans, vel	y-trans, vel	z-trans, vel	x-rot, vel	y-rot, vel	z-rot, vel

Six Subjects per Cell

Two 3-Minute Trials per Subject

Figure 3.2 - Experimental Design Matrix, Tracking in One Degree of Freedom

3.3 TRACKING IN THREE DEGREES OF FREEDOM

Another series of experiments was performed with tracking tasks in combinations of three degrees of freedom. Four of the six previously used subjects were used for these experiments. The target ball would move only in the three specified dof and the controlled ball would respond to input only in those same three dof.

Preliminary experimentation showed that when tracking in one dof at a time, x-translation and y-translation produced significantly less rmse than each of the other four dof. These two "good" degrees of freedom were combined with each of the other four "bad" degrees of freedom for four combinations of three dof:

1) x-translation, y-translation, z-rotation

2) x-translation, y-translation, y-rotation

3) x-translation, y-translation, z-translation

4) x-translation, y-translation, x-rotation

These combinations were performed with both acceleration and velocity inputs. The balanced latin square ordering of the experimental conditions gave the ordering for the four combinations shown in Table 3.2 (tr=translation, rot=rotation).

Order	Subject # 1	Subject # 2	Subject # 3	Subject # 4
1	x-tr,y-tr,z-rot	x-tr,y-tr,y-rot	x-tr,y-tr,z-tr	x-tr,y-tr,x-rot
2	x-tr,y-tr,y-rot	x-tr,y-tr,z-tr	x-tr,y-tr,x-rot	x-tr,y-tr,z-rot
3	x-tr,y-tr,x-rot	x-tr,y-tr,z-rot	x-tr,y-tr,y-rot	x-tr,y-tr,z-tr
4	x-tr,y-tr,z-tr	x-tr,y-tr,x-rot	x-tr,y-tr,z-rot	x-tr,y-tr,y-rot

Table 3.2 - Balanced Latin Square for Tracking in Three Degrees of Freedom

All four subjects were trained for one to two hours, receiving practice runs for each of the experimental conditions. During the training sessions the subjects tracked the target with the controlled ball in each of the combinations four times: two 2-minute trials with acceleration input and two 2-minute trials with velocity input for each dof.

After being trained the subjects returned twice more for two experimental sessions. Subjects # 1 and # 2 performed the tracking tasks with velocity input in their first experimental session and with acceleration input in the second session. Subjects # 3 and # 4 tracked with acceleration input first and velocity input in their second session. For each combination the subject would first track the target for a thirty second practice trial in order to adjust to the combination of dof. The practice trial was then followed by two data trials that lasted for three minutes each. The combination used for the data trials was the same combination used during the practice trial. Only the data from the data trials were used in the analysis. After the second data trial for a particular combination of dof, the subject would then proceed to the next dof performing the practice trial and the two data trials for that combination of dof. Figure 3.3 displays the test matrix for the experiments done with combinations of three dof.

Combination of Three degrees of freedom / control plant	x-trans, y-trans, z-trans	x-trans, y-trans, x-rot	x-trans, y-trans, y-rot	x-trans, y-trans, z-rot
Acceleration	x-trans, y-trans, z-trans, accel	x-trans, y-trans, x-rot, accel	x-trans, y-trans, y-rot, accel	x-trans, y-trans, z-rot, accel
Velocity	x-trans, y-trans, z-trans, vel	x-trans, y-trans, x-rot, vel	x-trans, y-trans, y-rot, vel	x-trans, y-trans, z-rot, vel

Four Subjects per Cell

Two 3-Minute Trials per Subject

Figure 3.3 Experimental design Matrix, Tracking in Three Degrees of Freedom

3.4 TRACKING IN SIX DEGREES OF FREEDOM

After the four test subjects completed the experiments for tracking in combinations of three degrees of freedom each subject performed a thirty second warm-up trial, tracking in all six dof at once followed by two 3-minute trials of tracking in all six dof at once. The subjects were trained in tracking in six dof at the end of the training session for combinations of three dof. They performed the experimental runs in six dof at the end of the experimental runs for combinations of three dof. If the subject was performing the acceleration session for three dof he would then track in six dof with acceleration control input. The same was true for velocity tracking. The tracking experiments in six dof provided rmse in each dof. This allowed an analysis to determine the relative operator performance of tracking in different degrees of freedom when all six were active at the same time.

4. EXPERIMENTAL RESULTS

The results presented in the following sections compared translations and rotations separately from each other. This was done due to errors in translation representing changes in distance in a certain direction that can be measured in inches or centimeters. In contrast, rotations represent angular movement that can be measured in radians. Since rotations and translations are measured in different units, rotational and translational rmse's were not compared directly in this analysis.

Appendix A contains all of the experimental data. The data were analyzed through an analysis of variance (ANOVA) (Snedecor and Cochran, 1967). The results were considered to be significant if the associated confidence level was greater than 95% or with $p <$ or $= .05$ (Chapanis, 1959). For dependent variables with more than two values that were found to make significant differences in performance, Newman-Keuls post-hoc testing was used to determine which values were significantly different from each other (Wall, 1986; Bruning and Kintz, 1977). Appendix B contains the results of the ANOVA.

4.1 TRACKING IN ONE DEGREE OF FREEDOM

These results represent the performance of the test subjects when tracking in only one dof at a time.

4.1.1 TRACKING IN ONE DOF - TRANSLATIONAL RESULTS

The analysis of variance (ANOVA) showed that the translational degrees of freedom made a significant difference in performance, $F(2,10) = 39.83$, $p < .0001$, the plant, i.e. acceleration or velocity control input, made a significant difference in performance, $F(1,5) = 20.25$, $p < .01$, and the interaction between translational degrees of freedom and plant made a significant difference, $F(2,10) = 11.92$, $p < .005$.

The rmse averaged over both control inputs (plants) for each dof were as follows:

degree of freedom	average rmse
x-translation	.0243
y-translation	.0234
z-translation	.0738

The Newman-Keuls post-hoc testing revealed that there was no significant difference between x-translation and y-translation tracking performance. There was however significant differences between x-translation and z-translation, and between y-translation and z-translation.

The average rmse over the three translational degrees of freedom for tracking with a velocity plant was .0284, for acceleration the average rmse was .0525.

The significant interaction between translational dof and plant is shown in figure 4.1. The average rmse's were:

condition	average rmse
x-translation, velocity	.0181
y-translation, velocity	.018
z-translation, velocity	.0492
x-translation, acceleration	.0305
y-translation, acceleration	.0287
z-translation, acceleration	.0984

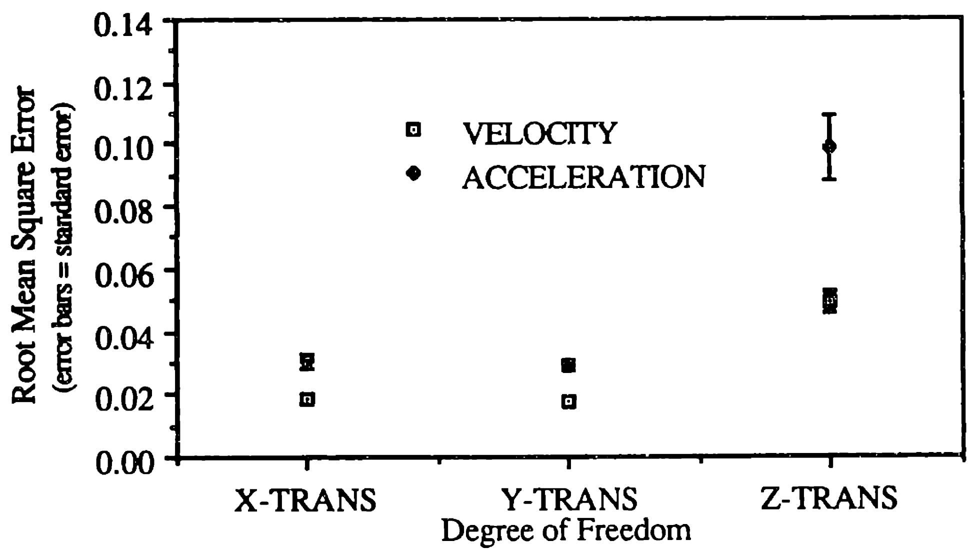

Figure 4.1 - Tracking in One DOF, Translational Results

Post-hoc testing revealed that there was not a significant difference between x-translation and y-translation for velocity or acceleration control. There was a significant difference between x-translation and z-translation and between y-translation and z-translation for both velocity and acceleration control. Further, for each degree of freedom there was a significant difference between tracking in that dof with velocity control and tracking in that dof with acceleration control.

4.1.2 TRACKING IN ONE DOF - ROTATIONAL RESULTS

The statistical analysis found that there was no significant difference in performance between any of the three rotational degrees of freedom when combined over acceleration and velocity control. The results were as follows:

degree of freedom	average rmse
x-rotation	.0469
y-rotation	.0413
z-rotation	.0394

Using acceleration or velocity control was found to make a significant difference in performance $F(1,5) = 19.15$, $p < .01$. For velocity the average rmse was .0266 and for acceleration the average rmse was .0586.

The interaction between rotational degree of freedom and plant was not found to make a significant difference in performance. The breakdown of average rmse for each condition was as follows:

condition	average rmse
x-rotation, velocity	.0272
y-rotation, velocity	.0266
z-rotation, velocity	.026
x-rotation, acceleration	.0667
y-rotation, acceleration	.0561
z-rotation, acceleration	.0529

Figure 4.2 shows the results for tracking in rotational degrees of freedom for velocity and acceleration plants.

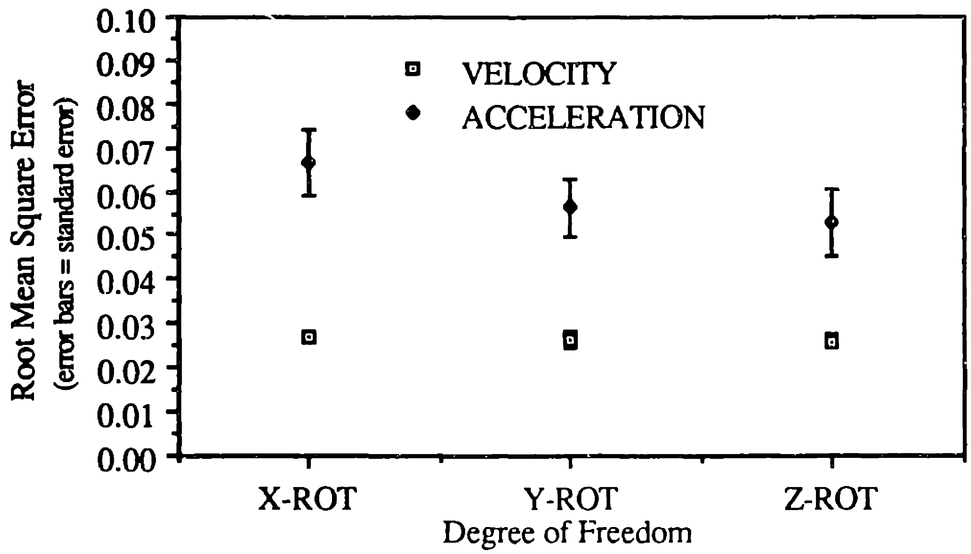

Figure 4.2 - Tracking in One DOF, Rotational Results

4.2 TRACKING IN COMBINATIONS OF THREE DOF

The four combinations of three dof were 1) x-translation, y-translation, z-translation; 2) x-translation, y-translation, x-rotation; 3) x-translation, y-translation, y-rotation; 4) x-translation, y-translation, z-rotation.

4.2.1 TRACKING IN THREE DEGREES OF FREEDOM AT THE SAME TIME

When subjects tracked with a combination of movement in x-translation, y-translation, and z-translation, and no rotational movement, the degree of freedom, control plant, and interaction between dof and plant made significant differences in performance.

The analysis of variance showed that degree of freedom made a significant difference in performance, $F(2,6) = 56.21$, $p < .0001$. Post-hoc testing revealed that x-translation and y-translation were not significantly different from each other but that x-translation and y-translation were both significantly different from z-translation. The results for tracking in the degrees of freedom averaged over velocity and acceleration control were:

Degree of Freedom	Average rmse
x-translation	.045
y-translation	.0468
z-translation	.0895

The control plant also significantly affected performance, $F(1,3) = 11.31$, $p < .05$. The average rmse with velocity control was .0695, with acceleration control it was .152.

The results for the significant interaction between degrees of freedom and control plant, $F(2,6) = 6.96$, $p < .05$ are listed below and graphed in figure 4.3.

condition	average rmse
x-translation, velocity	.029
y-translation, velocity	.0307
z-translation, velocity	.149
x-translation, acceleration	.0878
y-translation, acceleration	.0957
z-translation, acceleration	.273

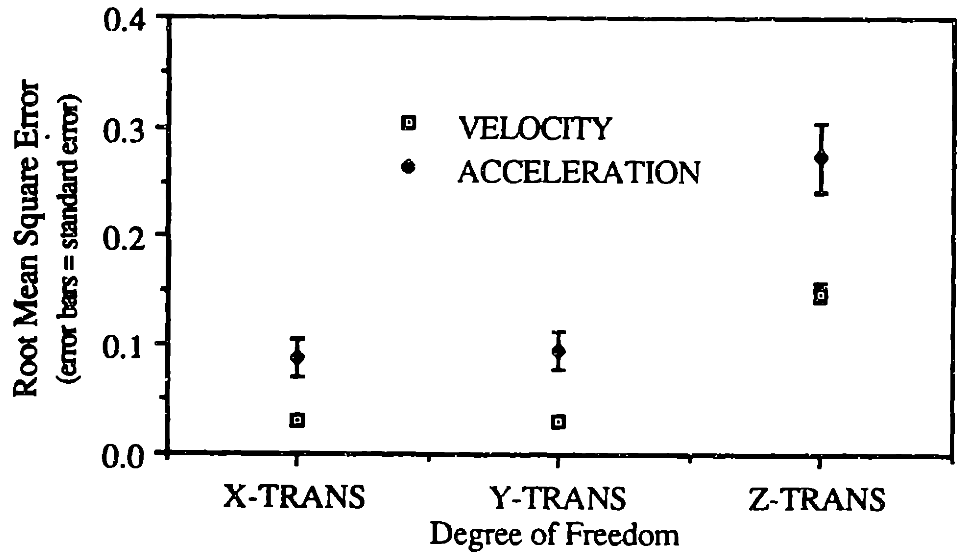

Figure 4.3 - Tracking in 3 DOF, Translational Results

Post-hoc testing showed that there was no significant difference between y-translation and x-translation for either a velocity or an acceleration plant. There was however significant differences between y-translation and z-translation and between x-translation and z-translation for both velocity and acceleration control plants. At each dof there was a significant difference between velocity and acceleration plant tracking.

4.2.2 TRACKING IN COMBINATIONS OF THREE DOF - ROTATIONAL RESULTS

When each rotational dof was combined with x-translation and y-translation, rotational dof made a significant difference in performance $F(2,6) = 5.11$, $p = .0507$ and the average rmse's were:

Degree of Freedom	Average rmse
x-rotation	.327
y-rotation	.304
z-rotation	.204

Post-hoc testing showed that there was no significant difference between x-rotation and y-rotation, but there was a significant difference between x-rotation and z-rotation and between y-rotation and z-rotation.

The control plant also produced a significant difference in tracking performance $F(1,3) = 9.99$, $p = .0509$. The average rmse for velocity control was .135, and for acceleration it was .421.

The interaction of rotational degree of freedom with control plant did not make a significant difference in performance. A summary of the results is shown in figure 4.4 and below:

Condition	Average rmse
x-rotation, velocity	.185
y-rotation, velocity	.154
z-rotation, velocity	.066
x-rotation, acceleration	.468
y-rotation, acceleration	.453
z-rotation, acceleration	.342

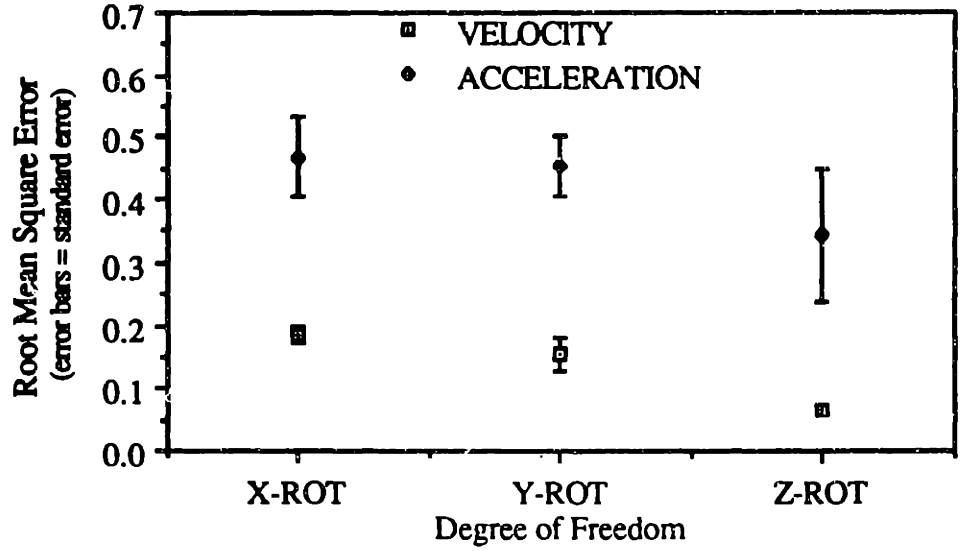

Figure 4.4 - Tracking in 3 DOF, Rotational Results

4.2.3 RESULTS OF TRACKING IN X-TRANSLATION AND Y-TRANSLATION WHEN COMBINED WITH OTHER DOFS

An analysis was done to determine the effects on x-translation and y-translation tracking when combined with the other dof: z-translation, x-rotation, y-rotation, and z-rotation. The objective here was to determine how x-translation or y-translation tracking performance was affected when combined with any of the other four dof.

In this section x-translation and y-translation are referred to as primary dof, and z-translation, x-rotation, y-rotation, and z-rotation as secondary dof.

As was found previously, the control was found to make a significant difference in performance, $F(1,3) = 38.21$, $p < .01$.

The interaction between the primary and secondary dof was also found to make a significant difference in tracking performance. The results for this interaction are displayed in figure 4.5. A summary of the averages for this interaction are shown below:

Primary dof	Secondary dof	average rmse
x-translation	z-translation	.0584
x-translation	x-rotation	.0444
x-translation	y-rotation	.0652
x-translation	z-rotation	.046
y-translation	z-translation	.0632
y-translation	x-rotation	.0525
y-translation	y-rotation	.0498
y-translation	z-rotation	.0523

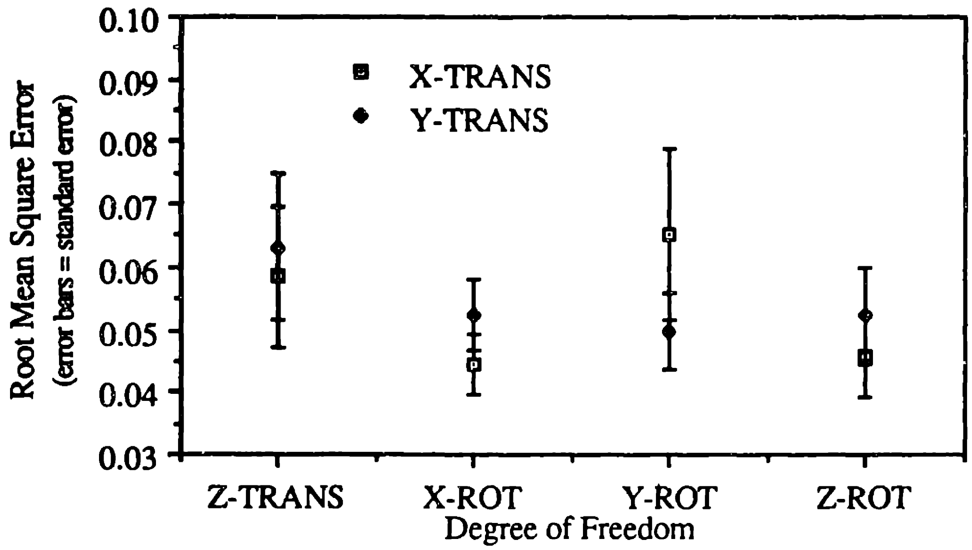

Figure 4.5 - Tracking in 3 DOF, Effects on X and Y-Translation

The analysis showed that when x-translation was combined with y-rotation, the resulting rmse for x-translation was significantly different than the rmse for x-translation when x-translation was combined with any of the other three secondary dof. When x-translation was combined with x-rotation the resulting rmse for x-translation was not significantly different when compared to x-translation and z-rotation, but was significantly different when x-translation was combined with the other two secondary dof. When x-translation was combined with z-translation, the rmse of x-translation for that combination was significantly different than the rmse for x-translation when x-translation was combined with any of the other three secondary dof.

There was a significant difference in tracking performance when y-translation was combined with z-translation compared to when y-translation was combined with the other secondary dof. When the other secondary dof (the three rotational dof) were combined with y-translation, the rmse's for y-translation that were not significantly different from each other.

When x-translation and y-translation were combined with z-translation, there was no significant difference between the rmse's for x-translation and y-translation. When the two primary dof were combined with any of the rotational secondary dof, there was a significant difference in the rmse's for x-translation and y-translation.

4.3 TRACKING IN SIX DEGREES OF FREEDOM

The following results are for tracking done with movement in all six degrees of freedom at the same time.

4.3.1 TRACKING IN SIX DOF - TRANSLATIONAL RESULTS

The analysis of variance revealed that translational dof, $F(2,6) = 77.94$, $p < .0001$, and control plant $F(1,3) = 256.6$, $p < .0005$ made significant differences in performance but that the interaction of translational dof with control plant did not.

Post-hoc testing for translational dof showed that there was not a significant difference between rmse for x-translation and rmse for y-translation, but there were significant differences in tracking performance between x-translation and z-translation and between y-translation and z-translation. The average rmse for each translational dof when tracking in all six dof at once are listed below.

Degree of Freedom	Average rmse
x-translation	.0872
y-translation	.112
z-translation	.298

The ANOVA also determined that the control plant made a significant difference in performance with the velocity plant producing an average rmse of .108 and acceleration an average rmse of .224.

The results are shown graphically in figure 4.6 with tracking in each dof graphed separately for velocity and acceleration control.

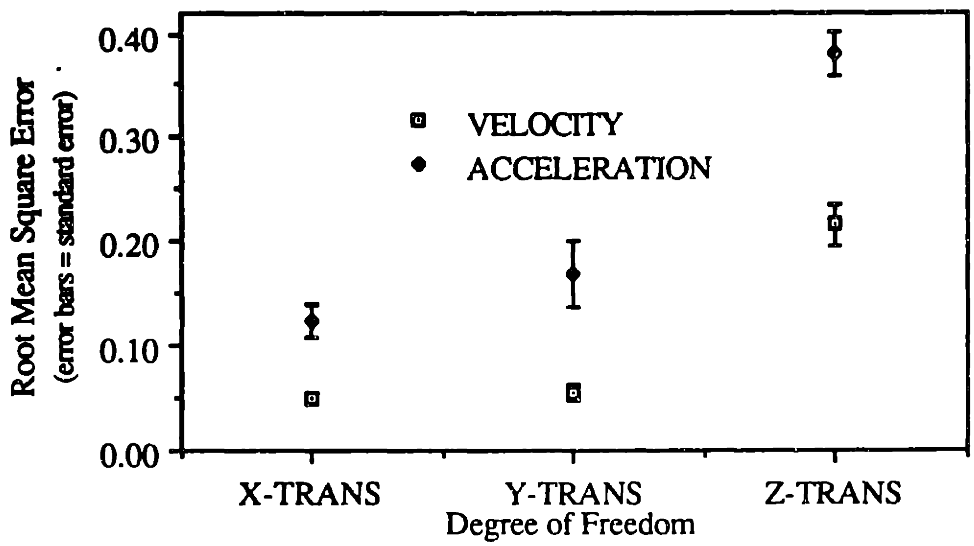

Figure 4.6 - Tracking in 6 DOF, Translational Results

4.3.2 TRACKING IN SIX DOF - ROTATIONAL RESULTS

The different rotational degrees of freedom did not make a significant difference in performance. The control plant did make a significant difference, $F(1,3) = 10.39$, $p < .05$. The average rmse for acceleration control was .803 and the average rmse for velocity control was .431. The interaction between rotational dof and control plant also produced a significant difference in tracking performance, $F(2,6) = 8.69$, $p < .05$. This interaction is presented in figure 4.7 and the data is shown below.

Condition	Average RMSE
x-rotation, velocity	.458
y-rotation, velocity	.429
z-rotation, velocity	.406
x-rotation, acceleration	.796
y-rotation, acceleration	.762
z-rotation, acceleration	.852

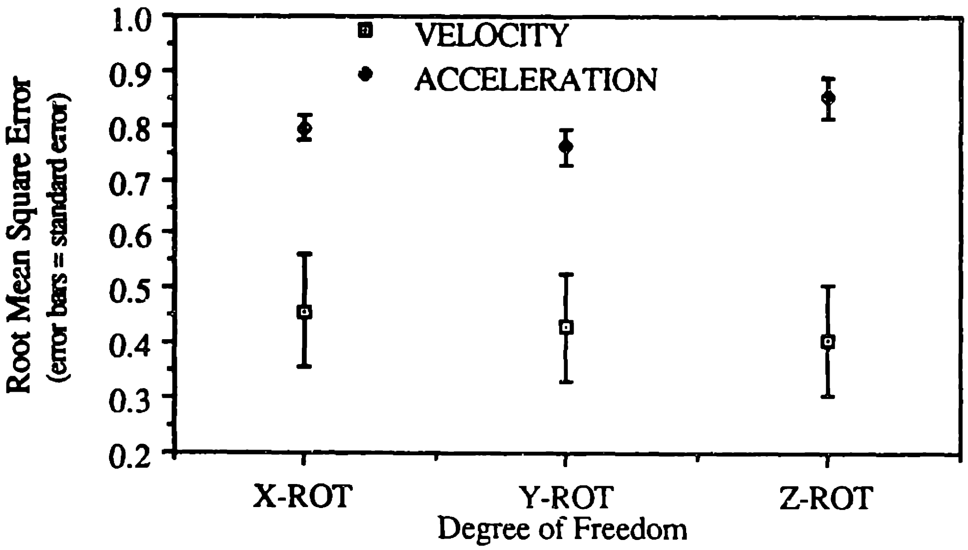

Figure 4.7 - Tracking in 6 DOF, Rotational Results

Post-hoc testing revealed that for tracking with the acceleration plant there was no significant difference between tracking in x-rotation and y-rotation, however there was a significant difference between x-rotation and z-rotation and between y-rotation and z-rotation.

For tracking with a velocity plant there was no significant difference between tracking in x-rotation and y-rotation or between y-rotation and z-rotation. There was a significant difference in tracking between x-rotation and z-rotation.

5. CONCLUSIONS

5.1 TRANSLATIONAL TRACKING CONCLUSIONS

For tracking in one degree of freedom at a time, there was no significant difference in tracking performance between x-translation and y-translation. However, z-translation produced significantly more tracking error than either x-translation or y-translation. Thus z-translation proved to be the most difficult translational dof in which to track when tracking in each dof independently.

A similar result was found when subjects tracked in combinations of three dof. There was significantly more rmse for z-translation when compared to x-translation or y-translation when subjects tracked in the three translational dof at once with no rotational movement. There was also no significant difference between x-translation and y-translation when tracking in the three translational dof only.

In section 4.2.3 an analysis was done examining the affects of the different combinations of three dof on x and y-translation. When x-translation was combined with either x-rotation or z-rotation, the resulting rmse for x-translation was significantly lower than when x-translation was combined with either z-translation or y-rotation. Further, the rmse for x-translation when combined with y-rotation was significantly greater than the rmse for x-translation when combined with any of the other three secondary dof. When y-translation was combined with z-translation there was significantly greater rmse for y-translation than when combined with any of the rotational dof. The three rotational dof produced y-translational rmse's that were not significantly different from each other. X-translation had significantly lower rmse than y-translation when the two were combined with x-rotation or z-rotation, however y-translation was significantly lower in rmse when the two primary were combined with y-rotation.

Summarizing the effects of the combinations of three dof on x and y-translation, x-translation fared best when combined with x-rotation or z-rotation and worst when combined with y-rotation. Y-translation performance was worst when combined with z-translation, and not significantly different when combined with any of the three rotational dof.

The tracking experiments in six degrees of freedom reinforced what was found in the one dof and three dof cases for translational dof. The results showed that x and y-translation performance were not significantly different from each other, and z-translation tracking performance was again significantly worse than either x or y-translation tracking performance.

5.2 ROTATIONAL TRACKING CONCLUSIONS

The only significant difference in tracking performance between the three rotational dof occurred when the subjects tracked in three dof at a time. For those experiments, z-rotation was found to have significantly less rmse than x-rotation or y-rotation. This evidence suggests that z-rotation may give the operator a better view than the other rotational dof. However, since tracking in one dof and six dof showed no significant differences in rotational dof, the advantages of z-rotation exhibited in the three dof case were interpreted conservatively.

5.3 VELOCITY AND ACCELERATION TRACKING CONCLUSIONS

The velocity input control plant was found to produce significantly better tracking performance than acceleration control for tracking in one, three, and six degrees of freedom for both translational and rotational dof tracking.

5.4 INTERACTIONS BETWEEN DEGREE OF FREEDOM AND CONTROL INPUT PLANT

When tracking in one dof, the interactions between translational dof and plant showed that acceleration control gave significantly higher rmse than velocity for each dof. In addition, z-translation yielded significantly more rmse than y-translation and x-translation for both velocity and acceleration inputs. This degradation in performance in the z-translation direction was worse with acceleration control than for velocity control. Thus acceleration control seemed to compound the problems that subjects had when tracking in z-translation more than when tracking in the other translational dof.

Similar results were obtained for translational tracking in three degrees of freedom. Acceleration control was worse than velocity control for each translational dof, z-translation had significantly more rmse than x and y-translation for both acceleration and velocity control, and z-translation performance was much worse during acceleration than velocity control.

For tracking in six dof, the significant interaction between rotational dof and control plant indicated that during acceleration control, z-rotation produced significantly more rmse than either of the other rotational dof. A different effect occurred for velocity control as z-rotation had significantly less rmse than x-rotation and a similar rmse as y-rotation. In addition when comparing the velocity plant versus the acceleration plant, acceleration control produced significantly more rmse than velocity control for each rotational dof.

5.5 RECOMMENDATIONS

All of the tracking experiments indicated that for translational tracking, z-translation resulted in poorer tracking performance than x or y-translation. The problems that subjects had with z-translation when compared to either x-translation or y-translation could have been due to changes in z-translation appearing to the subject as a change in size on the two dimensional display. This change in size was due to the z-axis being the axis coming out of the display screen making z-translation a movement of coming out of and into the screen. Conversely, both y-translation and x-translation represented changes in position of the target. Thus it appears that a change in position of a target on the screen was easier to determine and track than changes in size.

The problem with z-translation could be due to a lack of visual cues for stereopsis due to the two dimensionality of the display. If it were possible to provide the operator with additional two dimensional depth cues, perhaps performance would improve (Goldstein, 1988). The primary two dimensional depth views that the operator did have were a size difference between the target and controlled balls to tell which one was in front of which, a difference in color shading of the balls if one were in front of the other. The tracking took place in what appeared to be a room (see figure 2.2) and the walls provided some linear perspective. A previous study with this hardware and software showed that shadows from the balls against the grid floor of room did not significantly help performance (Anderson, 1987). Some other type of visual might help. A compensatory display that displayed the error for the z-direction might be helpful. An additional marking on target that could be more easily aligned with the controlled object might make tracking easier.

A way to compensate for the degradation in performance due to z-translation for a six dof tracking task would be to provide more information about the movement of the target for the z-direction. This might be accomplished by providing a measure of the movement to the operator. Maybe a readout of actual distance from the target and the rate at which it is changing would be helpful. This information could be exhibited somewhere on the display screen. Another possibility would be to provide an additional camera view if possible. If the movement in the z-direction could be shown with a different camera angle the motion may be more clearly seen and understood by the operator. The ability to switch between views or to have two views simultaneously available could help operator performance.

The analysis also showed that certain combinations of dof were better than others. Therefore if a target is moving in certain dof more than others, it would be wise to try and have a camera angle such that a good dof or combination of dof are displayed to the operator. For example, during the combinations of three dof, x-translation had less rmse when combined with y-translation and z-rotation than when combined with y-translation and y-rotation. Thus as was indicated in section 4.2.3 certain combinations are better than others. By determining what motions would be most prevalent and than adjusting the views so that the movement is displayed to the operator as dof that have acceptable performance, overall tracking performance would be improved.

As the subjects went from tracking in one to three to six dof there rmse's for each dof increased. This makes sense since tracking in more dof is more difficult than tracking in fewer dof. Controlling more things at the same time requires more of the operator and as a result is more difficult as reflected in the data.

Acceleration control input yielded higher errors than velocity control for every dof under every condition tested. The interactions between translational dof and control plant indicated that acceleration control had more negative affects on z-translation tracking than velocity control. Therefore when tracking with acceleration control it would be even more important to try to represent additional information about z-translation to the operator than with velocity control.

It also appears that acceleration control could make performance more unpredictable. For example, z-rotation was found to yield better performance than y or x-rotation when tracking in three dof. Further, when tracking in six dof z-rotation performance was significantly better than x-rotation for velocity control, however, z-rotation produced significantly more rmse than other rotations for acceleration control. Therefore when tracking in acceleration control not only can one expect performance to decrease significantly as compared to velocity control, but also one can expect that the performance may become more unpredictable.

The significant increases in rmse during acceleration control suggest that using manual tracking for velocity plants and more automated tracking for acceleration plants would be wise if that choice were available. A problem with acceleration control appeared to be that the subjects were not sure how much of an affect their input would have on the output of the movement of the controlled ball. Because a movement could continue indefinitely if not counteracted by another input direction, it was difficult to know just how far the ball would move in a degree of freedom when giving the input. The control ball would begin accelerating in a direction, and it was difficult for the test subjects to know what the extent of the acceleration would be. A possible solution to this problem could be the use of a predictive display that would immediately indicate the final output position of the controlled object for a given input to the hand controller. Such a predictive display should allow for a quicker reaction to what the actual system response would be and let the subject take corrective action more quickly thus decreasing error.

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APPENDIX A - EXPERIMENTAL DATA

Key:

x-trans = x-translation

y-trans = y-translation

z-trans = z-translation

x-rot = x-rotation

y-rot = y-rotation

z-rot = z-rotation

s.d. = standard deviation

TRACKING IN ONE DEGREE OF FREEDOM, VELOCITY PLANT

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-TRANS	X-ROT	Y-ROT	Z-ROT
1	1	0.02	0.0164	0.0366	0.0315	0.0244	0.0262
	2	0.0175	0.0191	0.045	0.0242	0.0279	0.0235
2	1	0.0136	0.0137	0.0304	0.0254	0.0176	0.0225
	2	0.0131	0.0145	0.0287	0.0227	0.0216	0.0228
3	1	0.0206	0.0236	0.0626	0.0298	0.023	0.0224
	2	0.0222	0.0156	0.0601	0.0245	0.0274	0.0246
4	1	0.018	0.02	0.0481	0.0298	0.026	0.0403
	2	0.019	0.0163	0.0613	0.0253	0.0179	0.019
5	1	0.0152	0.0155	0.0602	0.0271	0.0283	0.028
	2	0.0184	0.0166	0.0597	0.0199	0.0278	0.0259
6	1	0.0203	0.0219	0.0516	0.0326	0.0388	0.0256
	2	0.0189	0.0226	0.0463	0.0332	0.038	0.0307
MEAN		0.0181	0.018	0.0492	0.0272	0.0266	0.026
S.D.		0.00281	0.00335	0.0122	0.0042	0.00664	0.00542

TRACKING IN ONE DEGREE OF FREEDOM, ACCELERATION PLANT

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-TRANS	X-ROT	Y-ROT	Z-ROT
1	1	0.0313	0.0313	0.0914	0.0658	0.0434	0.0333
	2	0.0438	0.0229	0.088	0.0736	0.0534	0.0339
2	1	0.0201	0.02	0.0527	0.0523	0.0441	0.0306
	2	0.0201	0.0201	0.045	0.0467	0.0334	0.0309
3	1	0.0243	0.0251	0.077	0.0395	0.0513	0.0449
	2	0.0273	0.0334	0.079	0.0481	0.0549	0.0713
4	1	0.0293	0.0249	0.121	0.0402	0.037	0.0566
	2	0.0313	0.0278	0.0679	0.0468	0.0462	0.0331
5	1	0.0352	0.0364	0.149	0.0866	0.114	0.108
	2	0.0359	0.0341	0.149	0.0863	0.0841	0.0516
6	1	0.0323	0.035	0.136	0.121	0.0587	0.0426
	2	0.0345	0.0329	0.125	0.0935	0.0555	0.0976
MEAN		0.0305	0.0287	0.0984	0.0667	0.0563	0.0529
S.D.		0.00584	0.00593	0.0365	0.0257	0.0223	0.0264

TRACKING IN THREE DEGREES OF FREEDOM, VELOCITY PLANT: X-TRANSLATION, Y-TRANSLATION, Z-TRANSLATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-TRANS
1	1	0.0252	0.0327	0.131
	2	0.033	0.0359	0.127
2	1	0.0234	0.0269	0.146
	2	0.0214	0.0205	0.125
3	1	0.0312	0.0301	0.134
	2	0.0338	0.0429	0.187
4	1	0.0302	0.0299	0.174
	2	0.0341	0.0266	0.165
MEAN		0.029	0.0307	0.149
S.D.		0.005	0.00672	0.0237

TRACKING IN THREE DEGREES OF FREEDOM, VELOCITY PLANT: X-TRANSLATION, Y-TRANSLATION, X-ROTATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	X-ROT
1	1	0.0278	0.0323	0.14
	2	0.0386	0.0413	0.208
2	1	0.0201	0.0312	0.16
	2	0.0231	0.0268	0.134
3	1	0.0267	0.034	0.218
	2	0.0236	0.0331	0.193
4	1	0.0321	0.0326	0.225
	2	0.0293	0.0403	0.2
MEAN		0.0277	0.034	0.185
S.D.		0.00582	0.00476	0.0354

TRACKING IN THREE DEGREES OF FREEDOM, VELOCITY PLANT: X-TRANSLATION, Y-TRANSLATION, Y-ROTATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Y-ROT
1	1	0.0313	0.0287	0.164
	2	0.041	0.0325	0.148
2	1	0.0223	0.026	0.088
	2	0.0261	0.024	0.101
3	1	0.0263	0.0224	0.124
	2	0.0307	0.0257	0.135
4	1	0.0568	0.0623	0.315
	2	0.0321	0.0636	0.156
MEAN		0.0333	0.0357	0.154
S.D.		0.011	0.0171	0.0702

TRACKING IN THREE DEGREES OF FREEDOM, VELOCITY PLANT: X-TRANSLATION, Y-TRANSLATION, Z-ROTATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-ROT
1	1	0.0225	0.0241	0.0622
	2	0.0227	0.0231	0.0646
2	1	0.0186	0.0247	0.0488
	2	0.0183	0.0219	0.0446
3	1	0.0277	0.026	0.069
	2	0.0209	0.0231	0.0609
4	1	0.0336	0.0283	0.0829
	2	0.0459	0.031	0.093
MEAN		0.0263	0.0253	0.0658
S.D.		0.00941	0.00305	0.0161

TRACKING IN THREE DEGREES OF FREEDOM, ACCELERATION PLANT: X-TRANSLATION, Y-TRANSLATION, Z-TRANSLATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-TRANS
1	1	0.0595	0.0711	0.172
	2	0.0727	0.103	0.202
2	1	0.0358	0.0664	0.193
	2	0.0505	0.0571	0.21
3	1	0.192	0.207	0.386
	2	0.0916	0.0889	0.386
4	1	0.105	0.09	0.325
	2	0.0955	0.0821	0.306
MEAN		0.0878	0.0957	0.273
S.D.		0.0483	0.0473	0.0886

TRACKING IN THREE DEGREES OF FREEDOM, ACCELERATION PLANT: X-TRANSLATION, Y-TRANSLATION, X-ROTATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	X-ROT
1	1	0.0546	0.0558	0.22
	2	0.0412	0.0746	0.232
2	1	0.0583	0.0534	0.365
	2	0.0788	0.113	0.492
3	1	0.0593	0.0668	0.564
	2	0.0638	0.0639	0.505
4	1	0.0771	0.085	0.698
	2	0.0556	0.0565	0.669
MEAN		0.0612	0.0711	0.468
S.D.		0.0123	0.02	0.182

TRACKING IN THREE DEGREES OF FREEDOM, ACCELERATION PLANT: X-TRANSLATION, Y-TRANSLATION, Y-ROTATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Y-ROT
1	1	0.0479	0.0379	0.254
	2	0.0478	0.0523	0.354
2	1	0.0628	0.0824	0.396
	2	0.0815	0.0582	0.426
3	1	0.0794	0.0471	0.461
	2	0.0766	0.0486	0.457
4	1	0.234	0.106	0.61
	2	0.147	0.0791	0.669
MEAN		0.0971	0.064	0.453
S.D.		0.0635	0.023	0.134

TRACKING IN THREE DEGREES OF FREEDOM, ACCELERATION PLANT: X-TRANSLATION, Y-TRANSLATION, Z-ROTATION

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-ROT
1	1	0.0558	0.0827	0.225
	2	0.041	0.0573	0.134
2	1	0.0541	0.0715	0.161
	2	0.0413	0.0654	0.122
3	1	0.0906	0.103	0.238
	2	0.0576	0.061	0.211
4	1	0.0874	0.0988	0.869
	2	0.0973	0.0956	0.775
MEAN		0.0656	0.0794	0.342
S.D.		0.0227	0.0181	0.3

TRACKING IN SIX DEGREES OF FREEDOM, VELOCITY PLANT

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-TRANS	X-ROT	Y-ROT	Z-ROT
1	1	0.0549	0.068	0.25	0.558	0.542	0.644
	2	0.0476	0.0488	0.228	0.285	0.218	0.152
2	1	0.0319	0.0344	0.17	0.155	0.104	0.0912
	2	0.0348	0.033	0.196	0.146	0.096	0.0875
3	1	0.0663	0.0986	0.206	0.834	0.808	0.816
	2	0.0516	0.0504	0.118	0.909	0.711	0.686
4	1	0.0687	0.0503	0.256	0.46	0.567	0.4
	2	0.0538	0.0579	0.304	0.314	0.388	0.368
MEAN		0.0512	0.0552	0.216	0.458	0.429	0.406
S.D.		0.0131	0.0209	0.0572	0.292	0.272	0.285

TRACKING IN SIX DEGREES OF FREEDOM, ACCELERATION PLANT

SUBJECT #	TRIAL #	X-TRANS	Y-TRANS	Z-TRANS	X-ROT	Y-ROT	Z-ROT
1	1	0.138	0.357	0.393	0.833	0.862	0.823
	2	0.0949	0.0792	0.265	0.727	0.81	0.94
2	1	0.0819	0.116	0.403	0.689	0.578	0.609
	2	0.0678	0.124	0.454	0.769	0.708	0.929
3	1	0.153	0.174	0.372	0.869	0.839	0.918
	2	0.0908	0.107	0.316	0.873	0.69	0.879
4	1	0.174	0.188	0.426	0.791	0.781	0.794
	2	0.185	0.206	0.41	0.82	0.824	0.924
MEAN		0.123	0.169	0.38	0.796	0.762	0.852
S.D.		0.045	0.0877	0.0616	0.0657	0.0959	0.112

APPENDIX B - ANALYSIS OF VARIANCE RESULTS

Key:

tdof = translational degrees of freedom

rdof = rotational degrees of freedom

mdof = primary degrees of freedom (x-translation and y-translation)

odof = secondary degrees of freedom (z-translation, x-rotation, y-rotation, and z-rotation)

plant = acceleration/control plants

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	6	1 2 3 4 5 6
TDOF	3	1 2 3
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 36

Tracking in One DOF, Translational Results

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	35	0.03583961	0.00102399	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	35	0.03583961			0.00000000		0.04046528

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	5	0.00275395	.	.
TDOF	2	0.02002695	.	.
SUBJECT*TDOF	10	0.00251391	.	.
?LANT	1	0.00522127	.	.
SUBJECT*PLANT	5	0.00128906	.	.
TDOF*PLANT	2	0.00284256	.	.
SUBJECT*TDOF*PLANT	10	0.00119192	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*TDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TDOF	2	0.02002695	39.83	0.0001

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.00522127	20.25	0.0064

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*TDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TDOF*PLANT	2	0.00284256	11.92	0.0023

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ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	6	1 2 3 4 5 6
RDOF	3	1 2 3
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 36

Tracking in One DOF, Rotational Results

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	35	0.01799330	0.00051409	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	35	0.01799330			0.00000000		0.04259722

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	5	0.00370909	.	.
RDOF	2	0.00036324	.	.
SUBJECT*RDOF	10	0.00094014	.	.
PLANT	1	0.00925765	.	.
SUBJECT*PLANT	5	0.00241719	.	.
RDOF*PLANT	2	0.00026283	.	.
SUBJECT*RDOF*PLANT	10	0.00104317	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*RDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
RDOF	2	0.00036324	1.93	0.1953

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.00925765	19.15	0.0072

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*RDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
RDOF*PLANT	2	0.00026283	1.26	0.3251

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	4	1 2 3 4
TDOF	3	1 2 3
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 24

Tracking in Three DOF, Translational Results

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	23	0.20371643	0.00885724	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	23	0.20371643			0.00000000		0.11072917

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	3	0.01850657	.	.
TDOF	2	0.11969106	.	.
SUBJECT*TDOF	6	0.00638770	.	.
PLANT	1	0.04089527	.	.
SUBJECT*PLANT	3	0.01085036	.	.
TDOF*PLANT	2	0.00515995	.	.
SUBJECT*TDOF*PLANT	6	0.00222553	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*TDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TDOF	2	0.11969106	56.21	0.0001

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.04089527	11.31	0.0436

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*TDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TDOF*PLANT	2	0.00515995	6.96	0.0274

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ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	4	1 2 3 4
RDOF	3	1 2 3
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 24

Tracking in Three DOF, Rotational Results

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	23	1.05551811	0.04589209	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	23	1.05551811			0.00000000		0.27795833

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	3	0.25115865	.	.
RDOF	2	0.06805290	.	.
SUBJECT*RDOF	6	0.03998526	.	.
PLANT	1	0.49192067	.	.
SUBJECT*PLANT	3	0.14776913	.	.
RDOF*PLANT	2	0.00057265	.	.
SUBJECT*RDOF*PLANT	6	0.05605886	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*RDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
RDOF	2	0.06805290	5.11	0.0507

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.49192067	9.99	0.0509

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*RDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
RDOF*PLANT	2	0.00057265	0.03	0.9700

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	4	1 2 3 4
MDOF	2	1 2
ODOF	4	1 2 3 4
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 64

Tracking in Three DOF, Effects on X & Y Translation

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	63	0.06978320	0.00110767	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	63	0.06978320			0.00000000		0.05398281

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	3	0.00659287	.	.
MDOF	1	0.00001511	.	.
SUBJECT*MDOF	3	0.00103407	.	.
ODOF	3	0.00180804	.	.
SUBJECT*ODOF	9	0.00946654	.	.
MDOF*ODOF	3	0.00145704	.	.
SUBJECT*MDOF*ODOF	9	0.00037500	.	.
PLANT	1	0.03610000	.	.
SUBJECT*PLANT	3	0.00283427	.	.
MDOF*PLANT	1	0.00002889	.	.
SUBJECT*MDOF*PLANT	3	0.00106143	.	.
ODOF*PLANT	3	0.00143546	.	.
SUBJECT*ODOF*PLANT	9	0.00463568	.	.
MDOF*ODOF*PLANT	3	0.00150247	.	.
SUBJ*MDOF*ODOF*PLAN	9	0.00143632	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*MDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
MDOF	1	0.00001511	0.04	0.8476

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*ODOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
ODOF	3	0.00180804	0.57	0.6469

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.03610000	38.21	0.0085

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*MDOF*ODOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
MDOF*ODOF	3	0.00145704	11.66	0.0019

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*MDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
MDOF*PLANT	1	0.00002889	0.08	0.7937

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*ODOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
ODOF*PLANT	3	0.00143546	0.93	0.4656

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJ*MDOF*ODOF*PLAN AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
MDOF*ODOF*PLANT	3	0.00150247	3.14	0.0798

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ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	4	1 2 3 4
TDOF	3	1 2 3
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 24

<u>Tracking in Six DOF, Translational Results</u>

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	23	0.33179438	0.01442584	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	23	0.33179438			0.00000000		0.16572083

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	3	0.01028734	.	.
TDOF	2	0.21224505	.	.
SUBJECT*TDOF	6	0.00816925	.	.
PLANT	1	0.08146845	.	.
SUBJECT*PLANT	3	0.00095247	.	.
TDOF*PLANT	2	0.00846913	.	.
SUBJECT*TDOF*PLANT	6	0.01020270	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*TDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TDOF	2	0.21224505	77.94	0.0001

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.08146845	256.60	0.0005

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*TDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
TDOF*PLANT	2	0.00846913	2.49	0.1631

ANALYSIS OF VARIANCE PROCEDURE

CLASS LEVEL INFORMATION

CLASS	LEVELS	VALUES
SUBJECT	4	1 2 3 4
RDOF	3	1 2 3
PLANT	2	1 2

NUMBER OF OBSERVATIONS IN DATA SET = 24

Tracking in Six DOF, Rotational Results

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: RMSE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	23	1.61019295	0.07000839	.	.	1.000000	0.0000
ERROR	0	0.00000000	0.00000000		ROOT MSE		RMSE MEAN
CORRECTED TOTAL	23	1.61019295			0.00000000		0.61705625

SOURCE	DF	ANOVA SS	F VALUE	PR > F
SUBJECT	3	0.49420169	.	.
RDOF	2	0.00565379	.	.
SUBJECT*RDOF	6	0.01541766	.	.
PLANT	1	0.83240713	.	.
SUBJECT*PLANT	3	0.24039147	.	.
RDOF*PLANT	2	0.01644436	.	.
SUBJECT*RDOF*PLANT	6	0.00567686	.	.

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*RDOF AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
RDOF	2	0.00565379	1.10	0.3917

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
PLANT	1	0.83240713	10.39	0.0485

TESTS OF HYPOTHESES USING THE ANOVA MS FOR SUBJECT*RDOF*PLANT AS AN ERROR TERM

SOURCE	DF	ANOVA SS	F VALUE	PR > F
RDOF*PLANT	2	0.01644436	8.69	0.0169