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Interactive Displays for Trajectory Planning and Proximity Operations

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Rendezvous, docking, and other Space Station proximity operations (PROX OPS) will be conducted routinely in space. Real-time interactive visual aids and planning tools will be helpful, if not necessary, for future missions both in preflight training and on orbit. Two such displays, eivaN and Navie, are currently available for examination and human factors testing. A study was conducted in which data were collected from eight test subjects. Solution times for both devices decreased rapidly with experience. Neither fuel usage nor the number of waypoints (burns) decreased with experience. With Navie, medians of solution time and fuel consumption totaled over all subjects peaked at one of two starting points above the V-bar with monotonically decreasing values in both directions. This pattern did not appear with eivaN values. Since the docking tasks were fundamentally different with each device, and because Navie imposed more constraints on the users than eivaN did, the orbital mechanics effects had a more pronounced effect on the Navie results than on the eivaN data.

Introduction

PROXIMITY operations (PROX OPS) are defined as those activities occurring within a 1-km sphere of the Space Station. These include, but are not limited to, rendezvous, docking, rescue, and repair. Although the burns and trajectories for routine maneuvers such as departures and dockings are standardized and planned long in advance, in some cases this planning would not be possible. Such would be the case with an accident, lost piece of equipment, or a stranded astronaut.

Prior experimentation with docking operations revealed visualization and comprehension problems associated with orbital motion.[1] Orbital operations are inherently counterintuitive, partly because of non-linearities in the response characteristics of orbiting vehicles and partly because long-term effects of control actions are opposite to what one might expect; e.g., thrust in the direction of motion will increase the orbital period (resulting in apparent slowing of the vehicle being controlled) and vice versa. Because of the uncertainties involved with performing such maneuvers, an on-orbit facility must be available for plotting a recovery maneuver when time or other constraints prohibit using ground control computers. This ability would give the Space Station some additional autonomy required for long-term operation.

One system for planning maneuvers, known as Navie (a backward-looking trajectory plotting tool), is an interactive computer graphics program that runs on a Silicon Graphics IRIS workstation. Navie provides the operator with a third-person omniscient view of the Space Station and its surroundings. Target and chaser vehicles are illustrated on the screen with a least-fuel trajectory for a given mission duration connecting the two. Displays for fuel use, constraints (such as plume impingement), and time ticks are also presented. Given the mission objective and constraints, the astronaut constructs waypoints, or locations, in space and time until all constraints are satisfied.[2–4] Navie is a backward-looking device; the user controls the location of desired points in time and space and the computer calculates the required burns to connect them with a minimum fuel trajectory.

A forward-looking trajectory plotting program, eivaN, running on a Macintosh computer using Microsoft Excel®, is an alternative course plotting device. With eivaN, the operator inputs the burns in terms of magnitude, direction, and time into a spreadsheet. The computer then calculates and plots the resulting trajectory. Upon installation of each new burn, eivaN not only recalculates and presents the new trajectory but also continues to display the previous path before the addition of the new burn. In this way, the exact effect of each successive burn is demonstrated. Other advantages of eivaN are that its results can be printed and the exact parameters describing each burn in four dimensions (three space, one time) are readily available. This feature would be necessary to accomplish the transfer of data from the planning device to the flight vehicle. Also, exact position and velocity components are readily available for any point in time on any burn.[5–8]

Several other related programs have also been developed.[9,10]

Experimental Design and Protocol

Each subject performed four identical series of eight dockings with each planning device. Four subjects began with Navie (group 1) and four began with eivaN (group 2). Solution time, fuel consumption, and number of waypoints (for Navie) or burns (for eivaN) were recorded for each trial.

For the Navie part of the experiment, each subject was issued a training manual before the experimental sessions describing the device and its operation. Each test series consisted

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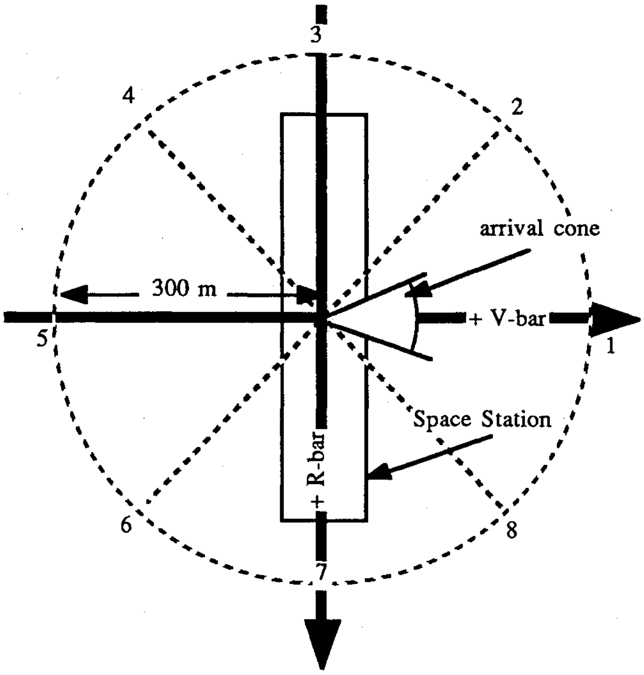

Fig. 1 Navie schematic and starting positions.

of the subject planning a docking maneuver to the Space Station located in a 300 km orbit from eight starting locations at an initial range of 300 m. These starting points were situated in the orbital plane at 45-deg intervals beginning with 0 deg located on the +V-bar axis (the velocity vector in the direction of motion). Positions 1–8 correspond to the position of an hour hand on a clock at 3:00, 1:30, 12:00, 10:30, 9:00, 7:30, 6:00, and 4:30. (See Figure 1).

The mission duration for each docking mission was fixed at 30 min; each subject installed waypoints in space and time to satisfy the mission constraints of approach velocity and angle. The only other constraint was that the flight path must not intersect an extended volume around the Space Station.

For the eivaN section of the experiment, each subject solved the same eight docking maneuver problems after reading a training manual. However, in this case, the maneuver time was not fixed at 30 min, and the subjects specified the burn parameters of component magnitudes and time rather than inserting waypoints. The subjects were restricted to a maximum of two burns, and the burn magnitudes for each component were restricted to between 0.1 and 9.9 m/s inclusive in increments of 0.1 m/s.

Figure 2 shows eivaN at the beginning of a trial starting from position 8. Figure 3 shows eivaN after the parameters for the first burn have been entered. Figure 4 shows eivaN after a solution has been found.

Results

Five of the subjects were male and three were female. Two of the subjects had previous experience with Navie and with proximity operations.

The raw data of solution times, fuel usage, and number of waypoints (or burns) for each device were statistically analyzed in several ways. Averages for each of the measurements were calculated for each of the four replications as well as for each of the eight starting locations. Comparisons of solution time averages for each device by subject were also performed.

Learning curves were also computed. A learning curve percentage is an exponential value relating the decay of a measured value of performance for every doubling of trials.[11] The average quantity (time, fuel, waypoints) for series 4 was divided by the corresponding value for series 2 and the same was done for series 2 and 1. These two values were then averaged together to arrive at learning curve percentage values by series. The same calculations were performed for the data arranged by starting location, and these learning curve values were then averaged to arrive at one value for each of the measured quantities for a learning curve value by starting location. Two learning curve percentage values were thus available for each value for each subject for each device for time, fuel, and number of waypoints (burns).

An example of a learning curve calculation is as follows. With consecutive data of 10, 8, 5, and 2, 2 is divided by 8, yielding 0.25, and 8 is divided by 10, producing 0.8. The average of 0.25 and 0.8 is 0.525. This would be considered a 53% learning curve.

Learning data as such were compared in several different ways. Learning by series was compared with learning by posi-

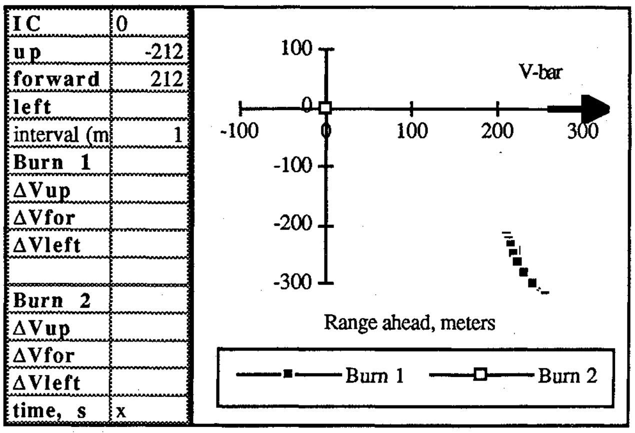

Fig. 2 eivaN at start of trial.

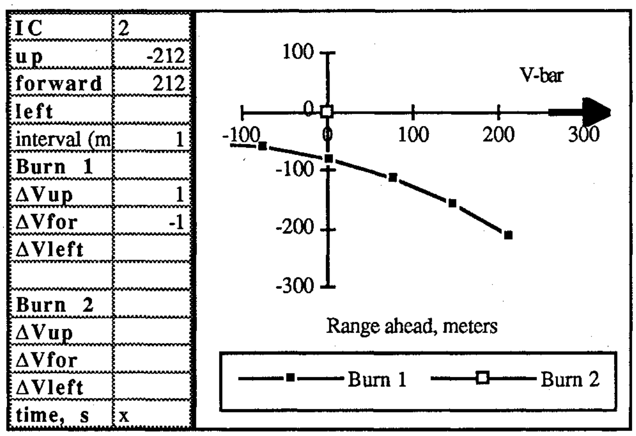

Fig. 3 eivaN after one burn has been entered.

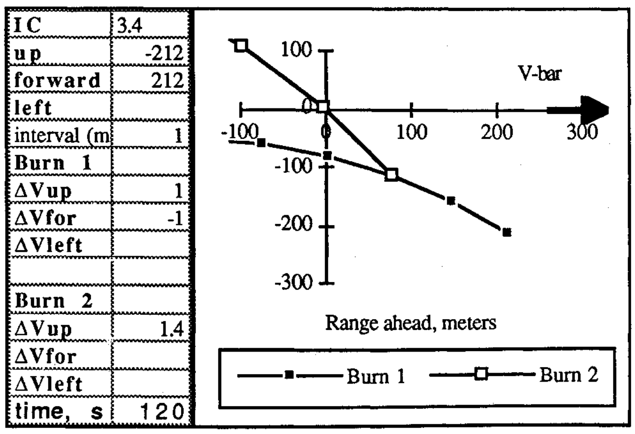

Fig. 4 eivaN after solution is completed.

tion, Navie learning was compared with eivaN learning, and first device learning was compared with second device learning.

Subjects learned significantly better by series than by position. With Navie, means [standard deviations (SDs)] were 63.0 (11.6) and 74.0 (12.3) for series and position learning, respectively ($p = 0.001$). With eivaN, means (SDs) for series and position were 73.5 (18.5) and 89.5 (24.9), respectively ($p = 0.006$). Comparisons of learning by device failed to yield significant results favoring one device over the other either by series or by position.

Learning data from both subject groups were also compared. Navie means (SDs) were 62.8 (14.4) and 63.3 (10.4) for group 1 and group 2 subjects, respectively. This difference was not significant at the 5% level. The same analysis was also performed with eivaN data. Averages (SDs) for eivaN were 89.0 (23.5) and 69.5 (19.6) for groups 1 and 2, respectively. Again, there was no significant difference at the 5% level.

EivaN solution time averages (SDs) were 84 (72) s for the Navie first (group 1) subjects and 100 (62) s for eivaN first (group 2) subjects. This difference was significant at the 5% level. The large standard deviations are more indicative of varying difficulties among starting points rather than spreads in data for any individual starting point. There were no significant differences in fuel or burn data between the two eivaN groups. Comparisons of Navie data between groups failed to yield any significance for any of the three measurements.

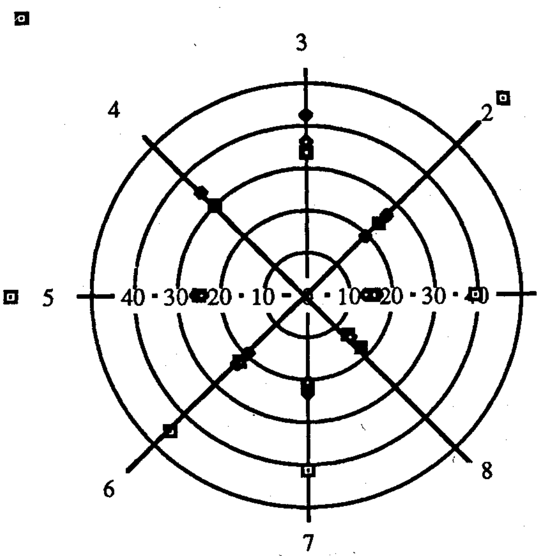

Fig. 5 Navie solution time medians by starting location.

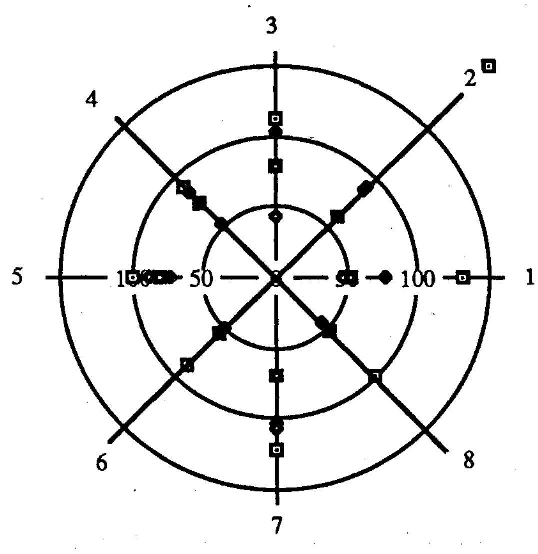

Fig. 6 eivaN solution time medians by starting location.

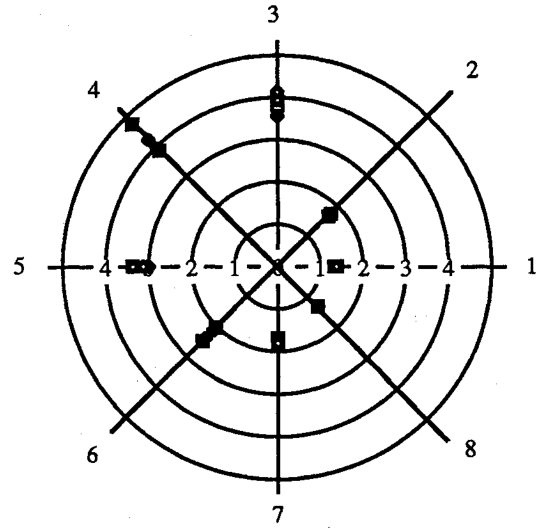

Fig. 7 Navie fuel consumption medians by starting location.

Data were also analyzed within subjects. Solution time averages (SDs) for the group 1 subjects for Navie and eivaN were 51 (94) s and 84 (72) s, respectively ($p < 0.001$). Solution time averages (SDs) for group 2 subjects were 48 (66) s and 100 (63) s for Navie and eivaN, respectively ($p < 0.001$). Both groups achieved significantly lower solution times with Navie than with eivaN.

Solution time, fuel consumption, and number of waypoints (burns) data were charted in polar coordinates according to initial conditions. Each data point comprises the median value for each series at that particular starting location.

Analysis of solution time data by starting location indicates which locations were most and least difficult from which to solve docking problems. Every subject found position 8 (4:30) to be the easiest with Navie. Positions 5, 6, and 8 (9:00, 7:30, 4:30) were each either first or second lowest in time with half of the subjects using eivaN. Seven of the subjects achieved worst or second worst scores starting from position 3 (12:00) using Navie. With eivaN, half of the subjects achieved worst scores starting from position 1 (3:00). These data are depicted in Figs. 5 and 6.

Fuel consumption averages were also compared with starting location. These data appear in Figs. 7 and 8 for Navie and eivaN, respectively. Dockings beginning from position 8 consumed first or second lowest amounts of fuel for each subject with Navie. Position 4 required highest or second highest consumption for seven subjects. With eivaN, position 7 scored lowest for four subjects but highest or second highest for three subjects, whereas position 4 consumed first or second highest amounts for half of the subjects. Thus, although docking missions beginning from position 4 consumed the most fuel for more subjects than any other position regardless of which device was used, the least fuel position was not the same for both devices.

Charts of the number of waypoints (burns) appear as Figs. 9 and 10 for Navie and eivaN, respectively. Position 1 required the least number of waypoints on Navie for every subject with positions 2 and 8 always either second or third lowest. Position 7 was always first or second highest. With eivaN, position 8 was always lowest and position 7 was always first or second highest.

Comparison of solution time with fuel consumption reveals a positive Spearman correlation with Navie and a negative correlation with eivaN. Correlation of the number of waypoints (burns) with solution time was positive in every case for every subject. The number of waypoints (burns) were also correlated with fuel consumption. See Table 1.

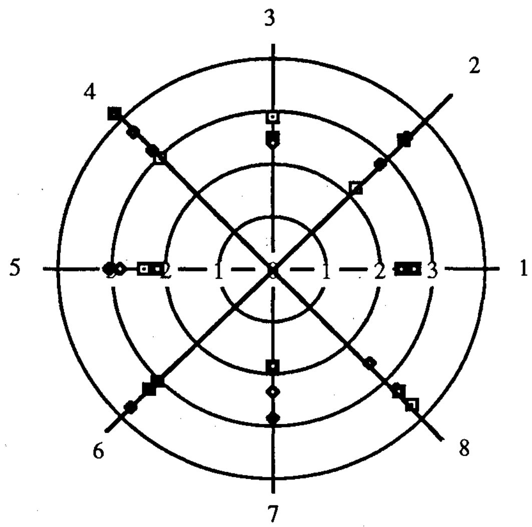

Fig. 8 eivaN fuel consumption medians by starting location.

Table 1 Correlation values

Correlation	Subject group	Spearman	p
Solution time and fuel consumption	Navie 1	0.477	0.001
	Navie 2	0.524	<0.001
	eivaN 1	−0.296	0.001
	eivaN 2	−0.384	<0.001
Number of waypoints (burns) and solution time	Navie 1	0.469	<0.001
	Navie 2	0.431	<0.001
	eivaN 1	0.401	<0.001
	eivaN 2	0.725	<0.001
Number of waypoints (burns) and fuel consumption	Navie 1	0.707	<0.001
	Navie 2	0.793	<0.001
	eivaN 1	−0.505	<0.001
	eivaN 2	−0.476	<0.001

Data Analysis and Discussion

Data from most of the subjects produced dramatic learning curves as far as solution time was concerned. Although a learning curve of 80% is generally considered typical for most activities, all subjects did better than this, with the best learning curve being 43% for solution time averages by series with eivaN and 45% with Navie. Five subjects achieved learning curves better than 80% with eivaN. Two of the three subjects with lower than 80% learning rates had had prior experience with PROX OPS and one of these developed eivaN. Enough learning probably occurred during these prior experiences to limit further learning during rigid experimentation. All eight subjects achieved less than an 80% learning curve with Navie.

Fuel data produced learning curves close to 100%. However, one subject's scores yielded curves as high as 190% and 230%. A learning curve greater than 100% indicates that performance decreased over time. Not only did subjects fail to learn to reduce fuel, but in several cases fuel consumption increased substantially with experience. It must be remembered, however, that subjects were not striving to minimize fuel but were trying to solve the problems in the least amount of time. The task was easier (lower solution time) when more fuel was used.

Learning curve data for number of waypoints and burns also were approximately, if not exactly, equal to 100% in every case. This indicates that the number of waypoints (burns) required to perform maneuvers remained very consistent over time. This was the case both by location and by series for both devices.

The data for solution time averages for Navie arranged by starting location suggest that docking difficulty increased from position 1 to position 3 and decreased monotonically from position 3 to position 8. Although all of the subjects attempted every docking in order from position 1 to position 8, which might lead one to attribute this decrease in solution time to learning, this hypothesis does not explain the increase in solution time found in progressing from position 1 to position 3. Also, each subject completed four identical series, and since learning by series was greater than learning by position, the data more likely indicate inherent position difficulty rather than intra-series learning or experience. The parallelism among the curves suggests the presence of a fixed proportionality constant among the series that decreases with learning.

Similar data for eivaN show no distinctive pattern. There was no trend as to which starting locations were most difficult from which to dock. The trend was evident with Navie because Navie's longer mission duration and final docking constraint made it more susceptible to orbital mechanics effects.

Charts of fuel consumption averages vs starting location also show monotonically decreasing values from a peak at position 4 with Navie; again, there was no clear pattern with eivaN data. It is interesting that the highest fuel consumption values were not obtained from starting positions 3 and 7. This is unusual because, analytically, starting positions located directly above and below the target require the largest initial velocity to accomplish a two-burn maneuver. The discrepancy most likely arises from the arrival cone constraint imposed on the trajectory.

The only extreme value that was consistent for all subjects with both devices was that position 7 required the largest

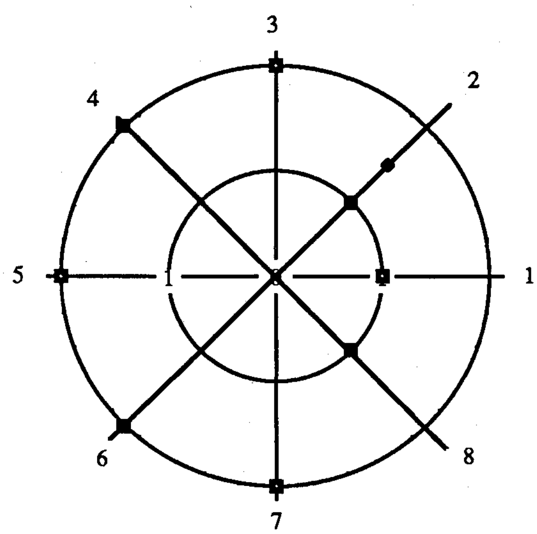

Fig. 9 Navie waypoints medians by starting location.

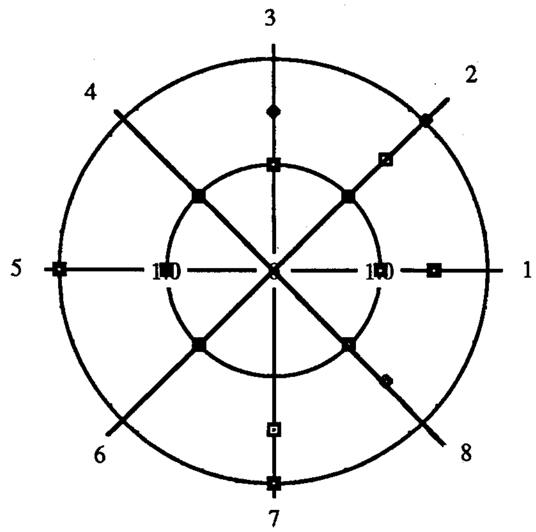

Fig. 10 eivaN burns medians by starting location.

number of waypoints (burns). This indicates an inherent difficulty with docking maneuvers beginning on the +R-bar (the radius vector toward the Earth), not in terms of planning time, but in actual flight, due to the high number of intermediate inputs required to arrive at the target. (Another problem with docking from the +R-bar not addressed by this study is the difficulty with stationkeeping due to the differences in orbital periods of two objects at different altitudes. Thrust must be applied constantly to maintain position.)

The primary reasons subjects required less fuel with Navie than with eivaN were that Navie required that a specified terminal velocity was not exceeded, it operated with a least-fuel algorithm, and its mission durations were longer so the average velocities were smaller. With Navie, the duration was fixed at 30 min, whereas with eivaN the mission times were as low as 2–3 min. Subjects paid for faster velocities on eivaN with increased fuel consumption. This result was also found in a spacecraft simulator study.[12,13]

Differences in end conditions combined with fundamental operational differences between the two devices caused greater waypoint usage with Navie than burn usage with eivaN. Waypoints were added by subjects with Navie to avoid collisions with the Space Station and to satisfy the arrival cone requirements of terminal angle and velocity. Since starting and final positions were already connected when Navie was initialized, without these additional requirements, all missions would have been successful without operator involvement.

Since with Navie the mission duration was fixed at 30 min, the only way to satisfy the end conditions was to install waypoints. With eivaN, the test subjects had a more direct control over the magnitude and direction of the burns and thus could frequently solve the missions with only one burn. Although subjects were limited to a maximum of two burns with eivaN, the median number of burns for all subjects was one.

The positive correlation of solution time with fuel consumption and number of waypoints with Navie is a result of the fact that installing waypoints to satisfy mission constraints causes both solution time and fuel to be consumed. Since Navie operates with a least-fuel algorithm, any change in course (by the addition of waypoints) is bound to increase fuel usage. Number of burns and solution time were positively correlated with eivaN. Since higher thrust levels tended to overpower orbital mechanics effects, solutions were easier to find (solution times were lower) when fuel consumption was higher. This caused a negative correlation between fuel and time with eivaN.

Another difference in the data from the two devices occurs in the comparison of correlations between fuel consumption and number of waypoints (burns). Again, Navie correlations were positive and eivaN correlations were negative. As explained earlier, Navie's course plotting algorithm guarantees a least-fuel trajectory so the amount of fuel consumed increases directly with the number of waypoints installed. With eivaN, however, fuel is used more effectively closer to the target than at a greater range because this limits the amount of time (and space) in which the orbital mechanics can play a role. At greater ranges, more fuel is required to overpower these effects than at closer ranges, otherwise the mission durations will be longer. Therefore fuel consumption decreases with increased number of burns.

Conclusions

1) Rapid learning of Navie and eivaN is possible where solution time is concerned.

2) With these missions, subjects do not learn solutions to individual starting points as well as they learn general device operation.

3) Docking missions from the +R-bar will probably require the greatest number of operator inputs.

4) Orbital mechanics effects cause the greatest interference with missions originating on the −R-bar.

References

[1]Brody, A. R., "Spacecraft Flight Simulation: A Human Factors Investigation into the Man-Machine Interface Between an Astronaut and a Spacecraft Performing Docking Maneuvers and Other Proximity Operations," Masters Thesis, Massachusetts Inst. of Technology, Dept. of Aeronautics and Astronautics, Cambridge, MA, April 1987 (see also NASA CR-177502, Sept. 1988).

[2]Grunwald, A. J., and Ellis, S. R., "Interactive Orbital Proximity Operations Planning System," NASA TP 2839, Nov. 1988.

[3]Ellis, S. R., and Grunwald, A. J., "The Dynamics of Orbital Maneuvering: Design and Evaluation of a Visual Display Aid for Human Controllers," *Proceedings of the FMP Symposium on Space Vehicle Flight Mechanics,* Luxembourg, AGARD-CP-489, 1989, pp. 29-1–29-13.

[4]Grunwald, A. J., and Ellis, S. R., "A Visual Display Aid for Orbital Maneuvering: Experimental Evaluation," *Journal of Guidance, Control, and Dynamics* (to be published).

[5]Brody, A. R., "EivaN: A Forward-Looking Interactive Orbital Trajectory Plotting Tool for Use with Proximity Operations (PROX OPS) and Other Maneuvers Description and User's Manual," NASA CR-177490, April 1988.

[6]Brody, A. R., "EivaN: An Interactive Orbital Trajectory Planning Tool for the Macintosh®, *Proceedings of the Society of Logistics Engineers/American Institute of Aeronautics and Astronautics Third Space Logistics Symposium,* Colorado Springs, CO, April-May 1990.

[7]Brody, A. R., "EivaN—An Interactive Orbital Trajectory Planning Tool," *COSMIC Software Catalog,* NASA CR-185888, 1990, p. 79.

[8]Brody, A. R., "EivaN: An Interactive Orbital Trajectory Planning Tool," *Journal of Spacecraft and Rockets,* Vol. 27, No. 6, 1990, pp. 681–683.

[9]Eyles, D., "A Computer Graphics System for Visualizing Spacecraft in Orbit," *Pictorial Communication in Virtual and Real Environments,* 1st ed., Taylor & Francis, London, England, UK, 1991, pp. 196–206.

[10]McCoy, W. K. Jr., and Frost, G. G., "Predictor Display Techniques for On-Board Trajectory Optimization of Rendezvous Maneuvers," Aerospace Medical Research Labs., AMRL-TR-66-60, Wright-Patterson Air Force Base, OH, May 1966.

[11]Koelle, H. H., "Fundamentals of Astronautical Engineering," *Handbook of Astronautical Engineering,* McGraw-Hill, New York 1961, pp. 1-61–1-62.

[12]Brody, A. R., "Quantitative and Qualitative Comparison Between Acceleration Control and Pulse Control in Spacecraft Docking," Masters Thesis, Dept. of Psychology, San Jose State Univ., San Jose, CA, May 1991.

[13]Brody, A. R., and Ellis, S. R., "Acceleration and Pulse Control in Simulated Spacecraft Docking Maneuvers," *Journal of Spacecraft and Rockets,* Vol. 28, No. 6, 1991, pp. 728–730.

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