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Visual Display Aid for Orbital Maneuvering: Experimental Evaluation

Arthur J. Grunwald*
Technion—Israel Institute of Technology, Haifa 32000, Israel
and
Stephen R. Ellis†
NASA Ames Research Center, Moffett Field, California 94035

An interactive proximity operations planning system, which allows on-site planning of fuel-efficient, multiburn maneuvers in a potential multispacecraft environment, has been experimentally evaluated. An experiment has been carried out in which nonastronaut operators with brief initial training were required to plan a trajectory to retrieve an object accidentally separated from a dual-keel Space Station, for a variety of different orbital situations. The experiments have shown that these operators were able to plan workable trajectories, satisfying a number of operational constraints. Fuel use and planning time were strongly correlated, both with the angle at which the object was separated and with the existence of spatial constraints. Planning behavior was found to be strongly operator-dependent. This finding calls for the need for standardizing planning strategies through operator training or the use of semiautomated planning schemes.

Introduction

THE proximate orbital environment of future spacecraft in low Earth orbit (LEO) may include a variety of spacecraft co-orbiting in close vicinity. Most of these spacecraft will be "parked" in a stable location with respect to each other, i.e., they will be on the same circular orbit. However, some missions will require unforeseen repositioning or transfers among them, as in the case of the retrieval of an accidentally released object. In this case, complex maneuvers are anticipated involving a variety of spacecraft that are not necessarily located at stable locations and thus have relative motion between each other. Furthermore, these types of maneuvers will have to meet stringent safety constraints, such as clearances from structures, restrictions concerning allowable departure and arrival velocities and angles, or plume impingement constraints.

The interactive proximity operations planning tool, in detail described in Refs. 1–4, enables the operator to deal with the highly complex and counterintuitive orbital situation by allowing him direct control over trajectory waypoints through an "inverse dynamics" algorithm and by enabling him to plan the trajectory through an iterative sequence of relatively simple independent solutions. Central in the trajectory planning process is the immediate visual feedback of trajectory shapes and operational constraints, provided by the continuously active background computation, transparent to the user.

This paper deals with the interaction of nonastronaut, but nonetheless highly professional operators (airline pilots, aerospace scientists), with the planning tool. It was of particular interest to investigate whether they could be familiarized quickly with orbital motions and complex orbital maneuvering, and whether they could plan workable trajectories, satisfying all operational constraints, within the reasonable time frame of several minutes. It was also of interest to investigate the variability in planning strategies of the various operators. In view of the considerable freedom left to the operator in the planning process, a large variability is expected. Although practice should reduce the variability for each operator individually as she gradually crystalizes her design strategy, it is far from certain whether all operator strategies will lead to the same solutions. The results of these experiments form the guideline for continued display developments, such as the inclusion of partially or fully automated optimization schemes, or standardization of training procedures.

Experimental Study

Purpose of the Study

An experimental study has been carried out to evaluate the operator's performance envelope while using the proximity operations planning tool. The purpose of this study was 1) to determine the time frame, after initial training of the operator,

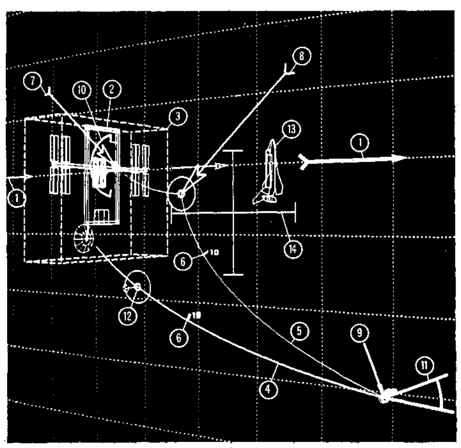

Fig. 1 Screen image of the main viewpoint of the proximity operations planning tool showing an incompletely planned mission for which three burns have been selected. The velocity vector or + V-bar is depicted by the arrows (1) pointing to the right on the central grid line. Note that the relative velocity vector on arrival, shown by the arrow (g) in the lower right of the viewport, is outside of the entry cone (11), indicating the acceptable range of relative velocity on arrival with the target craft.

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*Senior Lecturer, Faculty of Aero-Space Engineering; also National Research Council Senior Research Associate, NASA Ames Research Center, 1985–1987, Moffett Field, CA 94035. Member AIAA.

†Group Leader, Aero-Space Human Factors Research Division, Advanced Displays and Spatial Perception; also Staff Member, School of Optometry, University of California, Berkeley, CA 94720.

Table 1 Subject planning performance; subjects are instructed to minimize either fuel use *f* or planning time *t*

Subject	Instruction (t or f)	Planning time (s)	Fuel use (m/s)	Regression multiple correlation of fuel use vs violation score (R^2)
DB	t	526	3.966	0.214
ED	t	182	3.666	0.190
LK	t	572	5.602	0.403
RE	t	362	2.872	0.188
AJ	f	179	2.974	0.250
RO	f	317	4.764	0.379
SB	f	265	2.890	0.136
Average subject	t group	411	4.027	0.339
Average subject	f group	254	3.543	0.319
Average subject	both groups	343	3.820	0.349

$df = 86$.
All multiple correlations are significant at least at the $p < 0.01$ level.

necessary for carrying out a planning mission, randomly chosen from a broad spectrum of orbital situations; 2) to determine the factors that influence the operator's planning time, i.e., initial orbital situation, constraints; 3) to determine whether and to what extent the operator is able to optimize orbital fuel expenditure and determine the factors that influence the fuel use; 4) to investigate whether a tradeoff exists in operator performance between fuel use and planning time; 5) to investigate whether specific subject instruction to minimize either the planning time or fuel use affects this tradeoff; and 6) to identify planning strategies and determine the variability in the subject's planning performance.

Description and Design of the Experiment

The experiment was carried out on a Silicon Graphics IRIS 2400 workstation and the subjects interfaced with the system through a mouse and "soft" control buttons, programmed on the display. The experiment simulated the planning of a proximity operations retrieval mission of an object inadvertently released from a variety of positions along the main structures of a dual-keel Space Station configuration, in low 480-km altitude circular earth orbit. The chasing vehicle for the maneuver departed from a +V-bar location on the station and may be thought of as a craft attempting to recover an astronaut or object accidentally released with either zero or moderate (1.0 m/s) separation velocity v and that is drifting away under the influence of orbital mechanics forces. Out-of-plane separation velocity components of the target were randomly selected to be ±0.25 or ±0.5 m/s. The in-plane direction of the separation velocity vector v at release was randomly selected from eight possible directions, spaced in 45-deg intervals, about the +V-bar. The 10 possible orbital insertion points for the targets were distributed along the port keel of the Space Station from 200 m above the center of mass to 150 m below it and were also selected randomly to produce a total of 90 different recovery scenarios. The planned one-way flight time was 20 min and the maneuver took place during orbital daylight.

Description of the Task

The subject's task was to expeditiously plan a three-dimensional trajectory from a Space Station +V-bar departure port to rendezvous with the target, subject to departure and plume impingement constraints on the station, avoidance of the station's structure, and alignment of the relative velocity vector on rendezvous to fit within a 30-deg entrance cone. Such restrictions on the angles of departure and arrival might originate from structural constraints at the departure gate, or the orientation of the docking gate or grapple device at the target craft. Subjects were divided in two groups: the first group was instructed to minimize the fuel use, while keeping the planning time within acceptable limits; the second group was instructed to complete its planning task quickly (much as one would wish to walk across a room without wasting time), and not to worry about minimizing overall fuel use, although each subject was limited to a total velocity impulse v of 12-m/s maneuvering fuel.

Figure 1 illustrates a three-burn partial solution to one of the experimental scenarios. The main window shows the orbital plane with the orbital flight vector (1), the Space Station (2) with its spatial constraint envelope (3), target trajectory (4) and chaser trajectory (5), both with time markers (6) indicating the time in minutes after initiating the maneuver. Departure burn (7), intermediate burn (8), and retro burn at the target (9) are indicated by vectors, of which the length depicts the magnitude of the burn. Departure constraints are visualized by the bracketed arc (10) and arrival constraints by the approach cone (11). Both the departure arc and entrance cone

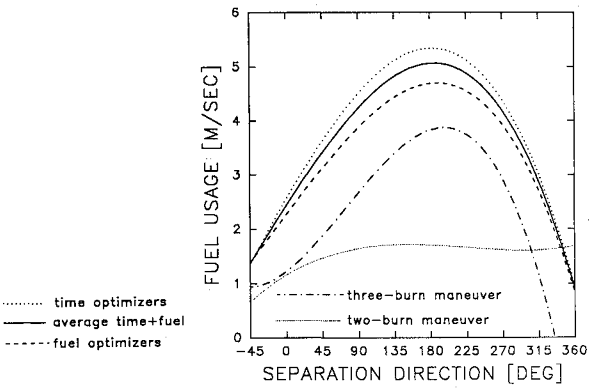

Fig. 2a Third-order regression curves for fuel usage vs target separation velocity vector direction. Analytical results of fuel usage for two- and three-burn maneuvers are also shown.

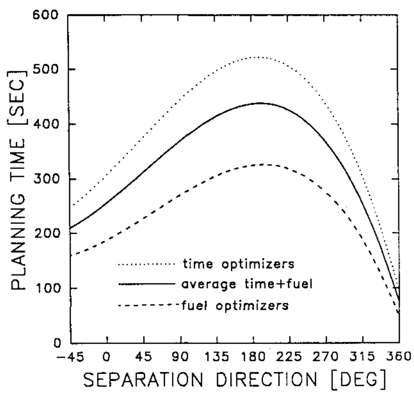

Fig. 2b Third-order regression curves for planning time vs target separation velocity vector direction.

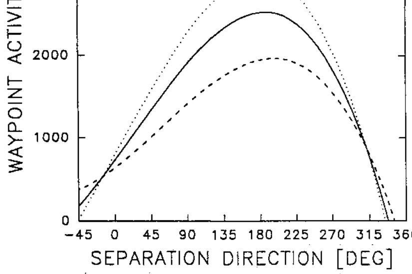

Fig. 2c Third-order regression curves for in-plane integrated waypoint displacement (*m*) vs target separation velocity vector direction.

Table 2 Correlation values (R^2) of third-order regression curves of separate direction vs fuel usage, vs planning time, and vs waypoint activity for the individual subjects

Subject	Instruction (t or f)	Regression multiple correlation of fuel use vs separate direction (R^2)	Regression multiple correlation of planning time vs separate direction (R^2)	Regression multiple correlation of waypoint activity vs separate direction (R^2)
DB	t	0.558	0.125	0.124
ED	t	0.285	0.054[a]	0.104
LK	t	0.297	0.023 ns	0.143
RE	t	0.531	0.007 ns	0.036 ns
AJ	f	0.452	0.070[a]	0.139
RO	f	0.269	0.150	0.120
SB	f	0.549	0.056[a]	0.096
Average subject	t group	0.524	0.094	0.231
Average subject	f group	0.493	0.124	0.146
Average subject	both groups	0.539	0.131	0.268

$df = 86$.
[a]Significant at the $p < 0.05$ level.
ns = not significant.
All others are significant at the $p < 0.01$ level.

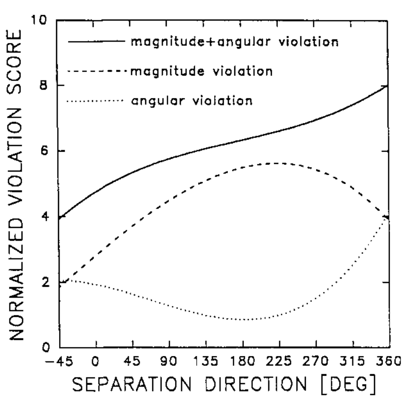

Fig. 3 Analytical results of third-order regression curves of violation scores vs the target separation velocity vector direction for a three-burn maneuver. The normalized magnitude violation curve shows a distinct maximum at the 225-deg separation angle, whereas the curve for the normalized angular violation score shows a minimum at 180 deg. The scores cannot be added and the magnitude violation is taken as the representative score.

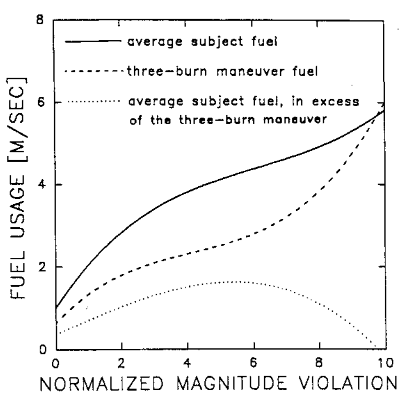

Fig. 4 Third-order regression curve of averaged-subject fuel use vs normalized magnitude violation score. The upward slope indicates that fuel use can be predicted from the violation score. The figure also shows the analytical regression curve for three-burn maneuver fuel use and the regression curve for the difference between the averaged-subject fuel use and 3-burn maneuver fuel use.

are drawn here brightly to indicate that departure and arrival velocity vectors have not yet been adjusted to fit the required constraints. Additional display attributes are the position of the target at intermediate waypoint time (12), additional vehicles like the orbiter (13), and a reference reticle in the center of the display (14).

Subject Background and Training

Seven subjects participated in the experiment. Three of them (ED, RE, RO) were airline pilots (DC-8, Boeing 737, P2, P5) of age 51–55 with 12,500–23,000 h of flight experience. One subject (DB) (age 54) was a retired navy pilot (A-4) with 5000 h of flight experience. The three remaining subjects (AJ, LK, SB) were nonpilot aerospace scientists aged 35–43. None of them, except two subjects (AJ, ED), were familiar with orbital operations and mechanics. Before beginning the experiment, the subjects carried out two 3-h training sessions usually completed in 1 day, in which they reviewed a training manual that interactively familiarized them with orbital mechanics and the various functions of the planning system. Finally, the manual guided them through a sample rendezvous planning mission in order to practice the display's controls and its operation.

Experimental Procedure

Data collection took about 8 hours and was generally spread across two days. Subjects were automatically presented through a UNIX C-shell script with the 90 rendezvous problems in four approximately equal groups of randomly ordered conditions. The following descriptive statistics were collected automatically by the IRIS computer: 1) planning time, 2) fuel use, 3) total number of way-points used, 4) operator activity such as number and type of operations and integral scores on the motion of waypoints in the planning process, and 5) a detailed account of constraint violations in the process, if any.

Results

Effect of Subject Instruction

Table 1 summarizes the average planning time and fuel use for 90 rendezvous planning missions, for each one of the subjects. The results show large variability between subjects. The subjects instructed to minimize fuel f on the account of planning time did not show significantly smaller fuel use [$F(1, 5) = 0.324$ $p < 0.594$] and those instructed to minimize the planning time t, did not have significantly shorter planning times, e.g., see RO and LK [$F(1, 5) = 2.033$ $p < 0.213$]. This indicates that the effect of subject instruction is highly masked by strong differences in basic planning strategy between the subjects. Table 1 also shows the average subject performance for the *t* group, *f* group, and both groups.

Effect of Target Separation Parameters

Target separation parameters include the location of target separation above or below the V-bar, and the magnitude and direction of the separation velocity vector direction.

Anova analysis revealed significant effects of separation location and separation velocity vector direction on fuel use, ($F=4.689$, $df=9,45$, $p<0.001$) and ($F=49.891$, $df=7,35$, $p<0.001$), respectively. Since large individual differences in performance were found, it was preferable to describe these and other results by subject-to-subject regression analysis, presented here. Figures 2a–c show third-order regression curves for fuel use, planning time, and in-plane integrated waypoint displacement (in m) vs target separation velocity vector direction, where the angle is measured positive in the upward direction from the positive V-bar direction. The average subject curves for a particular group, i.e., *t*, *f*, or both, are the regressions for a set of 90 values, obtained by averaging each one of the 90 rendezvous scenarios across the subjects in each group. Multiple correlation values for each one of the regressions are listed in Table 2. All curves show clear maxima about the 180-deg angle, i.e., objects released in the backward or negative V-bar direction. For target separation in this direction, the spacecraft will move initially backward and downward with respect to the Space Station. An attempted two-burn maneuver to recover the target craft will result in the chaser passing right through the Space Station spatial constraint envelope [attribute (3) in Fig. 1]. In order to avoid the envelope, a third intermediate burn is needed. The intermediate waypoint can be placed such that the trajectory passes either above or below the Space Station. Although the spatial constraints are satisfied, other constraints such as departure, arrival, plume impingement, and approach velocity constraints still have to be resolved. Figure 2a also shows analytical results of fuel use vs the separation velocity vector direction for two- and three-burn maneuvers. The location and time of arrival of the intermediate waypoint are chosen such that the trajectory just clears the envelope with minimum fuel cost. The minimum is empirically found to be unique. Although the fuel cost curve for the two-burn maneuver is almost flat, the curve for the three-burn maneuver shows a distinct maximum at about 180 deg. The difference between the curves can be attributed to the extra fuel cost involved in avoiding the Space Station envelope.

Figure 2a also shows that the average subject regression curves for the fuel usage, for the *t*, *f*, and both groups, are shifted upward with respect to the curve for the three-burn maneuver by a constant amount of 1 m/s. This indicates that the additional fuel needed to resolve the remaining constraint violations is independent of the target separation angle. The fuel use with the fuel optimizers is somewhat lower than that of the time optimizers.

A pronounced maximum at the 180-deg target separation velocity vector direction also appears in the regression curves for the planning time; see Fig. 2b. Surprisingly, the curve for the fuel optimizers is somewhat below that for the time optimizers, which indicates that instruction did not affect their absolute planning behavior. The strong increase in planning time for targets released in the backward direction can be attributed to both the time needed to position the third waypoint for clearing the structure, and the extra time needed to resolve other constraint violations resulting from this third

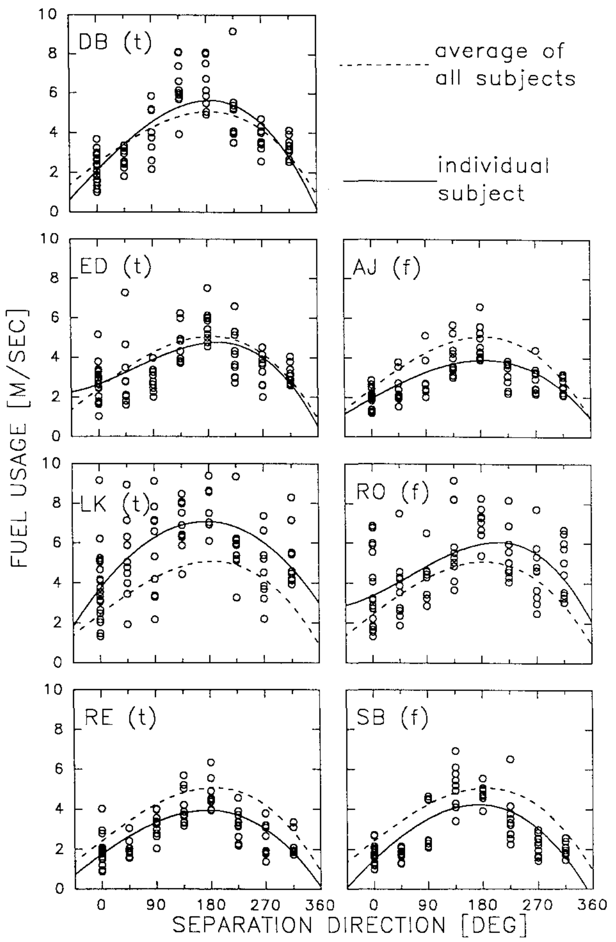

Fig. 5a Comparison of individual subject performance with performance, averaged over all subjects; third-order regression curves of fuel usage vs target separation velocity vector direction.

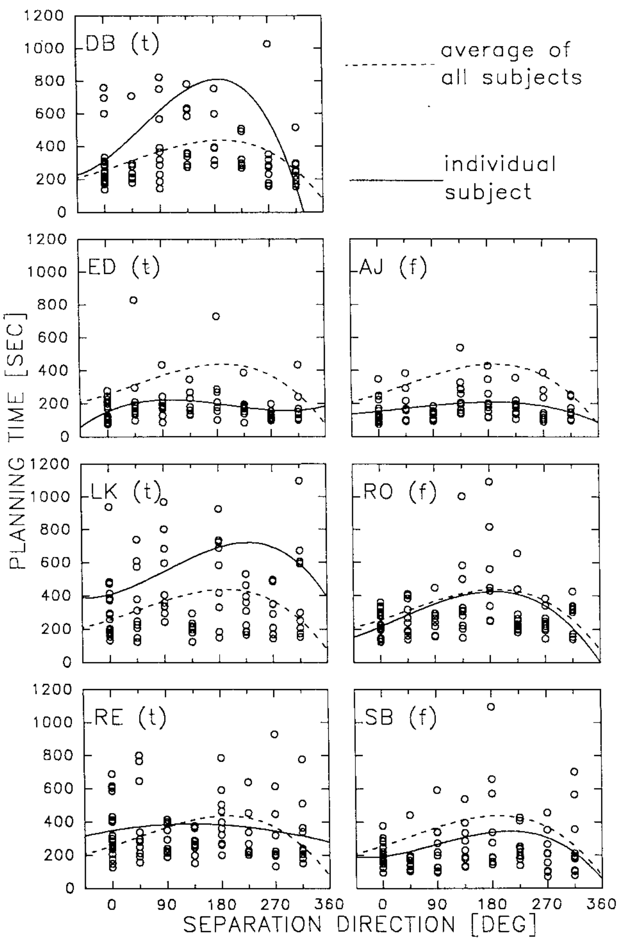

Fig. 5b Comparison of individual subject performance with performance, averaged over all subjects; third-order regression curves of planning time vs target separation velocity vector direction.

waypoint. A third waypoint placed considerably away from the unpowered two-burn trajectory will result in increased initial and terminal velocities and increased violations that, in turn, will demand longer planning times.

Similar maxima are found in the curves for the in-plane waypoint motion; see Fig. 2c. This indicates that for the targets separated in the backward direction, most of the additional planning time is devoted to the positioning of waypoints.

Measures for Predicting Fuel Expenditure and Planning Time

It is clear from the previous discussion that fuel expenditure and planning time will be closely related to the degree at which constraints are violated. A "violation score" has been composed as follows. Consider a three-burn maneuver with the third waypoint positioned such that the trajectory clears the spatial envelopes with minimum fuel. The resulting magnitude and angle violations at the departure gate and at arrival are treated separately. The amount of violation is normalized by dividing it by the allowable range and the normalized violations at departure and arrival are summed. Figure 3 shows the analytical results of the third-order regression curves of this violation score vs the separation angle. The normalized magnitude violation score shows a distinct maximum at the 225-deg angle and the normalized angular violation score a minimum at 180 deg. Added together, the effect of both scores is cancelled out, and the scores should therefore be treated separately. It is clear that the cost of avoiding the spatial envelope is primarily reflected in larger departure and arrival velocities and, therefore, a higher-magnitude violation. However, the effect of the third waypoint on the angular violation is highly

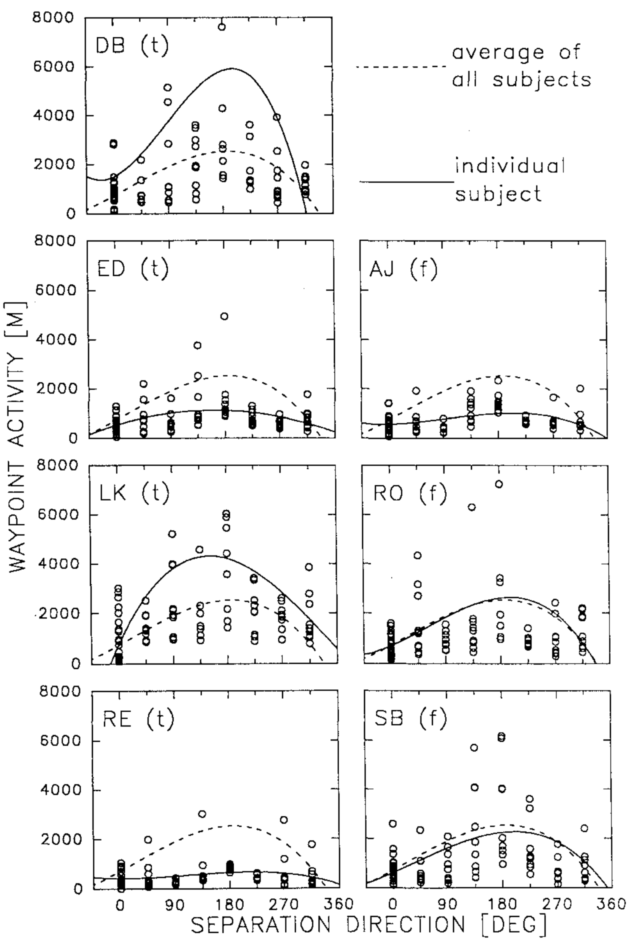

Fig. 5c Comparison of individual subject performance with performance, averaged over all subjects; third-order regression curves of in-plane waypoint activity versus target separation velocity vector direction.

case-dependent. The normalized magnitude violation is therefore taken as the representative violation score.

Figure 4 shows how fuel use can be predicted from the violation score. The third-order regression curve of fuel expenditure vs violation score, averaged over all subjects, shows a distinct upward slope. This slope is due, to a large extent, to the characteristic of the analytical curve for the three-burn maneuver. The fuel use, in excess to the three-burn maneuver fuel, is used for resolving the remaining constraints; see the third regression curve in Fig. 4. Until four units of normalized violation score, the slope is upward and almost constant. Although the predictive value of the violation score is generally low, i.e., $R^2 = 0.14$–0.40, the predictive third-order regressions were statistically significant for all individual subjects. See Table 1.

No significant correlation was found between the violation score and planning time, which means that the violation score is not useful in predicting the planning time.

Subject Planning Characteristics

In Figs. 5a–c, fuel use, planning time, and in-orbital-plane waypoint activity of the individual subjects are compared. The dotted line indicates the average subject third-order regression curve, whereas the solid line is this curve for a particular subject. The regression multiple correlation values of the various curves are listed in Table 2. The strongest correlation is found for the fuel usage curves and the weakest for the planning time. Although the subjects show the same inverted u-shaped regression curves, large individual differences are noticed. Subjects DB and LK show, in particular, longer planning times and in-plane waypoint activity for the "difficult" separation directions. However, with LK the fuel use at these directions is especially high. This means that DB and LK did not effectively use the additional planning time for obtaining lower fuel use.

On the other hand, AJ and ED show rather "flat" regression curves for the planning time and in-plane waypoint activity, which indicates that they did not spend more time on the difficult maneuvers. Fuel use at these directions is found to be better than average.

In general, a strong similarity is found between the curves for planning time and in-plane waypoint activity. This means that additional planning time is used in moving around waypoints. This is true, in particular, for the strongly shaped u-curves of DB and LK, but also for the flat curves of RE. With RE the waypoint activity is especially low. Planning behavior is thus found to be strongly situation- and subject-dependent.

Discussion

The results of the present and previous experiments[3] have shown that after an initially short training period, operators can manually quickly plan complex orbital maneuvers, satisfying all operational constraints, when their planning tool is adapted to their capabilities. It is nonetheless also clear that properly programmed automatic systems could also plan these maneuvers. These results can help set performance criteria for these automatic systems since they should at least be capable of producing feasible plans in less than 2 min to beat a manually determined plan. Incorporation of all the mission constraints, however, can greatly complicate and lengthen an automatic search since these constraints may be arbitrarily placed in space and, in some cases, may be discrete. The proposed interactive technique might assist automatic optimizers by choosing good initial conditions. Certain constrained random search strategies could be adopted if more efficient analytical methods do not work well; see Soller et al.[5]

However, it is also clear that no matter how the maneuver is planned, any astronaut flying a mission would want to foresee what the system has planned for her and be able to visualize her trajectory, if for no other reason but to monitor its unfolding as it is flown. Automatically generated trajectories will only be as good as the designer's hindsight in selecting optimization criteria and mission constraints. Unique mission features or failures may arise that require the custom-tailoring of a trajectory. Significantly, the mission-planning interface described in this paper also can serve as an interface to a mission "editor" that would allow an astronaut to visualize the automatically planned trajectories and edit them if necessary to suit her special requirements.

Absolute planning behavior is found to be strongly subject-dependent and hardly affected by subject instruction. On the other hand, fuel use and planning time are found to be affected by the target trajectory relative to spatial constraints. The higher multiple correlation values found for the fuel usage vs separation direction regression curves may be accounted for by the physical requirements associated with the mission, rather than human performance characteristics.

Violation scores on departure and arrival velocities would be useful in predicting the global amount of fuel use for a given mission. No measures have been found yet for predicting the necessary planning time.

The large variability in operator-planning behavior calls for standardizing planning strategies. At least three out of seven subjects were able to plan very fuel-efficient maneuvers within a reasonable planning time of about 300 s. Specific planning strategies of subjects with the best performance could be analyzed and used to compose a set of guidelines. These guidelines could be used either in an operator-training program or in expert systems to initialize or compose semiautomatic planning schemes.

The need for partial automatization in the planning procedure, such as the optimal positioning of a waypoint to clear a spatial envelope or satisfy departure or arrival constraints, is apparent when a uniform planning performance is desired over a wide range of situations and broad spectrum of operators. The automated system should be able to "suggest" a certain solution and quickly recompute a different solution when reviewed and changed by the operator. This will unburden the operator of planning time-consuming local optimizations. Efficient operator interaction with partially or fully automated planning schemes will require the development of local or global optimization schemes, for which the background computation time does not exceed several seconds.

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