Effect of an Anomalous Thruster Input During a Simulated Docking Maneuver

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An experiment was performed in the Space Station Proximity Operations Simulator at the NASA Ames Research Center. Five test subjects were instructed to perform 20 simulated remote docking maneuvers of an orbital maneuvering vehicle (OMV) to the space station in which they were located. The OMV started from an initial range of 304.8 m (1000 ft) on the space station's negative velocity vector (−V-bar). Anomalous out-of-plane thruster firings of various magnitudes (simulating a faulty thruster) occurred at one of five ranges from the target. Initial velocity, range of anomalous burn, and magnitude of anomalous burn were the factors varied. In addition to whether the trial was successful, time and fuel to return to a nominal trajectory, total mission duration, total fuel consumption (delta *V*), failure rate, and time histories of commanded burns were recorded. Analyses of the results added support to the hypothesis that slow approach velocities are not inherently safer than their more rapid counterparts. Naive subjects were capable of docking successfully at velocities faster than those prescribed by the "0.1% rule" even when a simulated faulty thruster disturbed the nominal trajectory. Little to no justification for slow approach velocities remains from a human-factors standpoint.

Introduction

THE docking of two spacecraft is a complicated task whose failure could result in the loss of mission, vehicle, or crew. Spacecraft have typically been flown at small relative velocities in rendezvous and docking maneuvers both to increase safety margins in the event of an incorrect burn and to minimize plume impingement and fuel consumption. Currently, astronauts are instructed in the use of a "0.1% rule," which suggests that the approach velocity be no greater than 0.1% of the range to the target per second. (At a range of 1000 ft, the approach velocity would be 1 ft/s. After 100 s, the vehicle would arrive at a range of 900 ft and the rate would be reduced to 0.9 ft/s.[1]) By decreasing the relative velocity with which one vehicle approaches another, demands upon reaction time are relaxed and workload is simultaneously (and proportionately) reduced as the number of required inputs per unit time decreases. However, surveys of aircraft and workload literature reveal that too low a workload may be just as dangerous as too high a workload.[2,3] Small approach velocities produce long mission durations where inactivity may lead to reduced attention, or sustained vigilance may lead to excessive fatigue. Long mission durations also may prove to be inordinately expensive in an operational space station era in terms of the time the crew are using to dock and not performing other duties. (However, fuel costs may obscure any such advantage for nominal missions.) Previous research revealed no statistically significant increase in failure rate with increased velocity; failure rate was more dependent upon a subject's risk profile than the velocity at which his/her docking maneuver began.[4,5]

In general, very little human factors research in the area of piloting space maneuvers has been documented in the U.S. space program.[4-16] Analytical engineering tests have been used to generate rules of thumb and verify strategies from a systems point of view without regard to man-in-the-loop considerations. This study is part of a series seeking to rectify that situation and is directed toward developing a unified theory and comprehensive data base for human-performance aspects of spacecraft control.

Current and future work is concerned with determining the feasibility of expanding the operational performance envelope to include more rapid dockings at higher average velocities without increasing the probability of failure. The Soviets have also expressed a desire for manual control to enable them to "operate in (a) wider range."[17] Quicker dockings are important not only for increasing productivity but also for improving the likelihood of a successful rescue of a stranded crewperson or spacecraft low on consumables. In nominal missions, saving time at the expense of fuel may not be cost effective. However, contingencies may arise when the cost of time is extreme as in a rescue operation. This research is geared toward discovering the fastest safe docking times should rapid docking be required.

Methods and Apparatus

The Space Station Proximity Operations Simulator at NASA Ames Research Center is a real-time flight simulator with which researchers have been studying docking maneuvers and other proximity operations for several years. It consists of three windows on which computer graphics images of stars and orbiting vehicles are presented, a three degree-of-freedom (DOF) hand controller, and other assorted controls and displays.[7,14] The windows face the minus velocity vector (−V-bar) of a space station in a 270-nm orbit about the Earth. From this perspective, X is positive through the operator's back, Y is positive to the left, and Z is positive down.

Five test subjects (three male, two female) each performed 20 simulated docking maneuvers commencing from 304.8 m

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Table 1 Initial conditions for 20 trials

Initial velocity, m/s	Range, m	Magnitude, m/s
1.9	85	0.5
0.9	45	0.8
1.9	85	0.5
1.9	20	0.5
3.6	85	0.5
0.9	125	0.8
0.95	45	0.2
2.9	45	0.8
1.9	85	1.0
2.9	45	0.2
2.9	125	0.2
1.9	85	0.5
1.9	85	0.5
1.9	85	0.0
1.9	85	0.5
1.9	150	0.5
0.3	85	0.5
2.9	125	0.8
1.9	85	0.5
0.9	125	0.2

(1000 ft) on the − V-bar. The trials began at one of five initial velocities: 0.3, 0.9, 1.9, 2.9, 3.6 m/s. A faulty thruster was simulated during each run by an anomalous out-of-plane burn of a pre-established magnitude at a pre-established range. The magnitude of the anomaly was one of five delta Vs (0.0, 0.2, 0.5, 0.8, 1.0 m/s) and occurred at one of five ranges (20, 45, 85, 125, 150 m) from the target. The subjects were cautioned to be wary of an unexpected incident but, until the first trial containing an anomaly, did not know what form the anomaly would take. A response surface methodology arrangement was used to reduce the total number of initial conditions from $5 \times 5 \times 5 = 125$ to 20.[18] Each subject started from 20 initial conditions (see Table 1), but in different random orders.

A successful docking was operationally defined as satisfying the following range and rate conditions upon contact with the space station at a range of 2 m from the station's center of mass: axial velocity no greater than 0.15 m/s, up/down and right/left range no greater than 0.23 m from center, and up/down and right/left velocity no greater 0.6 m/s.[19] In addition to whether the docking was successful, total mission duration, fuel consumption (measured in delta V), time out-of-plane ("away time"), out-of-plane fuel ("Y delta V"), and temporal/spatial histories of pilot burns were recorded for each simulated mission. Also, two derived quantities known as "reserve time" and "radial delta V" were obtained by subtracting a reference time/fuel from the mission duration/fuel consumption values.[4,5]

Results

Figure 1 shows the burn history vs range on the x axis for a typical trial for one of the subjects. The initial velocity was 0.9 m/s, and an anomalous burn of 0.8 m/s occurred at an x range of 125 m. For this trial, total mission duration was 498 s, total velocity increment (delta V) was 7.51 m/s, away time was 249 s, and Y delta V was 1.88 m/s. Figure 2 shows an expert pilot's response to the same initial conditions. The expert pilot's superior response is more likely due to several years' intensive experience with simulated spacecraft docking maneuvers than any innate ability. Mission duration, delta V, away time, and Y delta V were all lower than the test subject's with values of 380 s, 4.92 m/s, 9 s, and 1.32 m/s, respectively. While both trials were successful, the expert used fuel more effectively and efficiently as evidenced by the lower total velocity increment and by the smoother, and less active, burn history plots. He also recovered from the anomaly in under 4% of the test subject's time and then focused on slowing down the vehicle to satisfy the final docking conditions. Also, although mission duration generally varies inversely with fuel consumption (more fuel is required to travel faster and reduce time), the expert managed to reduce overall time without expending additional fuel by using every burn efficiently and minimizing pilot-induced oscillations.

Multiple regression analyses were performed on the data to determine the existence of any statistically significant effects. Analyses were performed not only on the whole data but also on the data after points outside the semi-interquartile range (outliers) had been removed, and after data associated with unsuccessful attempts were removed. Initial velocity, range, magnitude, and trial were the independent variables analyzed in each case.

As in earlier studies,[4,5] two variables, "reserve time" and "radial velocity increment," were derived from the mission duration and delta V data since increases in initial velocity generally "force" the mission durations to decrease and the fuel consumption to increase. Reserve time was calculated by dividing the initial range by the initial velocity and subtracting this value from the measured mission duration. In this way, the effect of the initial velocity is somewhat removed from the measurement, and what is left is the time the test subject reserved to successfully accomplish the task. The radial velocity increment values were obtained by subtracting the starting and stopping delta V and the Y delta V from the total delta V.

Two other variables were created to evaluate the final three-axis range and rate parameters as something besides the binary successful/unsuccessful. "Squared" was computed by summing the squares of the terminal range and rate values along the three axes. "Abs" is the sum of the absolute differences

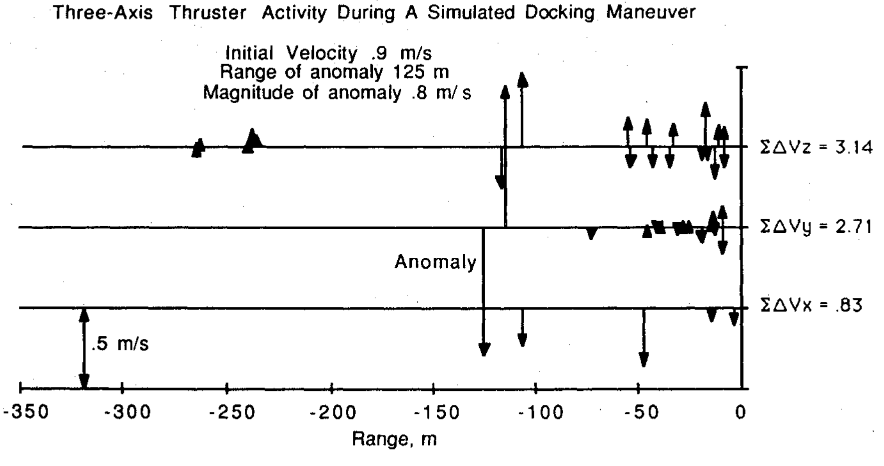

Fig. 1 Thruster commands (naive pilot).

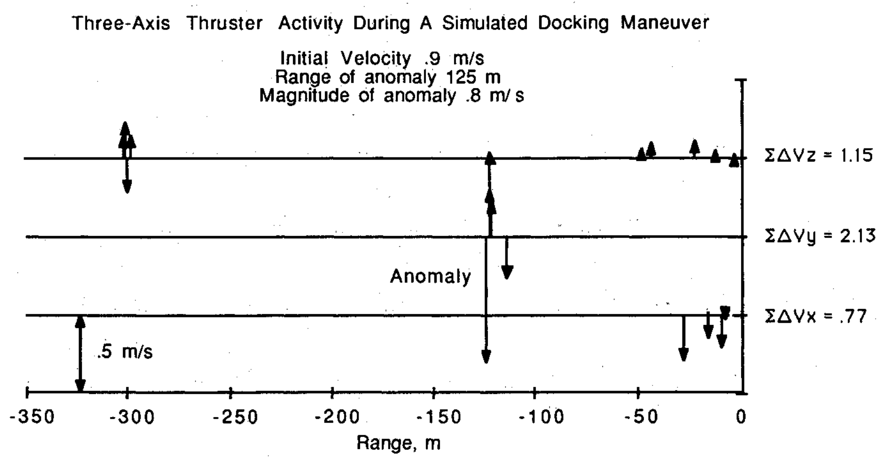

Fig. 2 Thruster commands (expert pilot).

between the actual terminal range and rate values and those required for a successful docking:

$$\text{Squared} = Y^2 + Z^2 + X\text{rate}^2 + Y\text{rate}^2 + Z\text{rate}^2$$

$$\text{Abs} = -\{[\text{Abs}(Y) - 0.23] + [\text{Abs}(Z) - 0.23] + [\text{Abs}(X\text{rate}) - 0.15] + [\text{Abs}(Y\text{rate}) - 0.06] + [\text{Abs}(Z\text{rate}) - 0.06]\}$$

Since the inclusion of outlying data points greatly compressed most of the data, these points were removed and regression analyses were recalculated. Removing outlying data points served to reduce the variance of the data and increased the likelihood of statistical significance.

A list of all statistically significant effects from response surface analysis appears in Table 2.

T-tests were also performed between data collected from successful docking missions and those collected from unsuccessful missions. The only variable for which there was a statistically significant difference was trial (4.20, $P < 0.001$), whose average was 12 for the successful missions and 8 for the unsuccessful.

Discussion

As in earlier studies without anomalies, mission duration was inversely related to initial velocity.[4,5] This relationship is not surprising considering that the faster one travels, the less time a trip of a given distance will take. The fact that this relationship was preserved when the anomalous thruster firings were included means that subjects did not slow down from fast initial velocities in order to recover from the "accident." Starting off at a high velocity caused the shortest mission durations despite the occurrence of anything unusual. Apparently, enough time was available for recovery even at an initial velocity as high as 3.6 m/s.

Removing the outliers, thereby decreasing the variance of the data, revealed a practice effect: trial became a significant factor determining mission duration. Some practice effect was expected but the scatter of all of the raw data points obscured it. Removing the data associated with the unsuccessful runs eliminated the practice effect while maintaining the velocity effect. Since practice both increased the likelihood of success and decreased the mission duration, removing the unsuccessful runs also eliminated the long duration runs, thereby eliminating a perceived practice effect when the data from the unsuccessful runs were removed.

Vehicles should pay for accelerating to, and decelerating from, higher velocities with higher fuel consumption (delta *V*). In the earlier study, there was a direct linear relationship between velocity increment and initial velocity as intuition would suggest. However, in the current experiment, delta *V* was solely a function of trial indicating a practice effect. Apparently, the inclusion of the anomalies destroyed the effect of velocity on delta *V*.

Delta *V* data without outliers not only showed a velocity effect but also indicated an effect based upon the magnitude of the anomalous burn and omitted an effect based upon experience. Clearing out the spurious data left two expected relationships: the velocity increment increased with initial velocity and with magnitude of the anomaly. Removing the data collected from the unsuccessful missions left only the magnitude effect.

Away time was correlated with magnitude. That is, the larger the magnitude of the out-of-plane burn, the longer it took to recover to the same plane as the space station. This effect disappeared when the outliers were removed but existed when only the unsuccessful data were removed. Since away time is bounded on the bottom by 0, removing the high, outlying data points eliminated any chance for the high away times to be associated with the high magnitudes.

Y delta *V*, like total delta *V*, exhibited a practice effect when all of the data were included but had only a magnitude effect when the outliers were removed. However, unlike total delta *V*, *Y* delta *V* had an effect of trial when the data collected from the unsuccessful missions were ignored. The trial effect is only evident when the outliers are included in the calculation.

Squared and Abs both displayed a velocity effect when all of the data were used, and neither showed any main effects when the unsuccessful data were removed. Squared had both a magnitude and a trial effect when the outlying data were removed, whereas Abs had only a trial effect.

The *t*-tests revealed only one statistically significant difference between the data collected from successful missions and those from the unsuccessful: subjects were more likely to have a successful mission toward the end of their experimental session. Although both Squared and Abs were derived from the range and rate parameters on impact, neither parameter was significantly different for a successful mission than an unsuccessful one. Although both values exhibited a velocity effect implying that velocity had some impact on the accuracy of the docking, this effect was not related to success at all. Velocity played no role in the success of the mission. In further corroboration, the *t*-test performed on velocity had a statistic of 0 with a *P* value of 1 indicating a 0% assurance that the populations were distinct.

Table 2 Significant effects

Dependent variable	Significant factor(s)	t-statistic	P
Total data			
Mission duration	Initial velocity	−5.43	<0.001
Velocity increment	Trial	−2.78	0.006
Y Velocity increment	Trial	−3.18	0.002
Z Velocity increment	Trial	−2.77	0.007
	Initial velocity	−2.12	0.036
Squared	Initial velocity	−2.08	0.040
Abs	Initial velocity	2.35	0.021
Without outliers			
Mission duration	Initial velocity	−5.59	<0.001
	Trial	2.55	0.013
Velocity increment	Initial velocity	3.93	<0.001
	Magnitude	3.16	0.002
Y Velocity increment	Magnitude	5.04	<0.001
Reserved time	Initial velocity	2.30	0.024
	Trial	2.53	0.013
Squared	Magnitude	2.01	0.047
	Trial	−2.43	0.018
Abs	Trial	2.69	0.009
Successful runs			
Mission duration	Initial velocity	−3.27	0.002
Velocity increment	Magnitude	2.41	0.020
Y Velocity increment	Magnitude	2.15	0.036
	Trial	−2.22	0.031
Z Velocity increment	Magnitude	2.49	0.016
Away time	Magnitude	2.24	0.029

Conclusions

As in earlier studies, researchers were unable to justify utilization of the 0.1% rule or any other flight profile requiring an arbitrarily slow approach velocity from a human-factors point of view. Not only did faster approach velocities fail to decrease safety during nominal operations, the presence of an anomalous thruster firing during the mission did not alter this result. Examination of human-factors considerations allows the operational flight envelope of a vehicle docking to a space station, or any other object, to be expanded to permit more rapid and lower duration missions.

Although engineering considerations, such as fuel consumption (cost), overwhelmingly demonstrate the value of slow missions, should fuel be made from waste water[20] or some other source thereby decreasing its cost, a least-time solution would become a least-cost solution as well. Also, for a vehicle and/or pilot with 10 minutes worth of consumables remaining, a 60-minute docking maneuver is not very helpful. An understanding of the fastest safe-docking technique will always be necessary for contingencies that will inevitably arise. Highly trained NASA pilot-astronauts with a mandatory minimum of 1000-h jet experience should have no trouble exceeding the performance values measured here. The safe operating envelope of space vehicles can now be expanded, providing the ability to rescue a crewmember or vehicle low on consumables.

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