# REMOTE OPERATION OF AN ORBITAL MANEUVERING VEHICLE IN SIMULATED DOCKING MANEUVERS

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## ABSTRACT

Simulated docking maneuvers were performed to assess the effect of initial velocity on docking failure rate, mission duration, and $\Delta v$ (fuel consumption). Subjects performed simulated docking maneuvers of an orbital maneuvering vehicle (OMV) to a space station. The effect of the removal of the range and rate displays (simulating a ranging instrumentation failure) was also examined. Naive subjects were capable of achieving a high success rate in performing simulated docking maneuvers without extensive training. Failure rate was a function of individual differences; there was no treatment effect on failure rate. The amount of time subjects reserved for final approach increased with starting velocity. Piloting of docking maneuvers was not significantly affected in any way by the removal of range and rate displays. Radial impulse was significant both by subject and by treatment. NASA's "0.1% rule", dictating an approach rate no greater than 0.1% of the range, is seen to be overly conservative for nominal docking missions.

## INTRODUCTION

The relative motion of Orbital Maneuvering Vehicles (OMVs) with respect to a space station is very difficult to visualize because of non-linearities in the governing equations of motion. For example, purely posigrade thrusts ultimately yield upward and then backward motion with respect to a "stationary" target such as a space station. Conversely, retrograde burns ultimately produce downward and forward motion. These paths are curvilinear and it is possible to "bounce" one's way around an orbit. While these burns also alter the original period, purely radial thrusts--which also provide fore and aft relative motion--do not affect the vehicle's orbital period. Simulation experiments are necessary to better understand pilot response to these non-intuitive phenomena.

## BACKGROUND

Proximity operations (PROX OPS) are defined as any and all activities occurring within a one kilometer sphere of the space station. Among these are rendezvous, docking, and rescue maneuvers. Simulations (and actual performance) of rendezvous and docking maneuvers began in the Gemini era in preparation for the two docking maneuvers required for a manned mission to the moon. These operations were performed slowly to increase safety margins in the event of an incorrect burn and to minimize fuel usage. The procedures were designed to minimize risk at the expense of time. The fact that a rendezvous may require anywhere from several hours to several days to perform[9] or that a docking may take as long as several hours was not a concern in the Gemini and Apollo programs. Mission durations were set to be long enough to accomplish all mission objectives. If, due to a miscalculation or exceptional pilot performance, a maneuver was completed in less time than allocated, free time had essentially just been created. A job queue as such did not exist.

The space shuttle/space station environment will be highly operational to support sustained human productivity on orbit. Retrieval and re-insertion of satellites and other orbital missions will become routine. Every hour a crewperson is spending on a docking maneuver is an hour s/he is not spending on some other task. There is a financial consideration in addition to the productivity issue. To date, the monetary cost of a crewmember's time has not been given much consideration in the U.S. space program. Recently, the value of $35,000 was cited as the cost of an hour of astronaut time on-orbit.[2] NASA guidelines stipulate that a crewperson on the space station will monitor all manned approaches in addition to the pilot in the vehicle so this one hour docking maneuver is actually worth $70,000.[9] Since others on both the station and the shuttle may be passively monitoring all or part of the approach, the cost of a one hour docking maneuver may easily rise to beyond $150,000 not including the cost of fuel and other expendables. With an estimated 5-6 dockings of the shuttle to the station each year for support[12], the annual cost of docking to the space station may approach $1,000,000. The addition of OMV, orbital transfer vehicle (OTV), and ESA free flyer traffic will further increase this cost.

Current shuttle rendezvous guidelines are very conservative suggesting that a "0.1% rule" be followed. This rule dictates that the shuttle's relative closing velocity with respect to the space station (or some other target) should be limited to a value no greater than 0.1% of its range per second. For example, at a range of 1000 meters, the velocity should be 1 meter per second. After 100 seconds, the shuttle arrives at a range of 900 meters and the range rate is decreased to 0.9 m/s.[10] A docking from an initial range of one kilometer would take about one hour to complete if this guideline were followed. This is an

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arbitrary rule of thumb designed to afford the pilot a sufficient safety margin with which to successfully perform the maneuver. Very little rigorous human factors studies were performed to determine what the man-in-the-loop requirements or restrictions might be.

Another area in which data suggest the need for further evaluation of current docking guidelines is workload. Workload has been under intensive scrutiny in the airline industry for some time. Here, crew inactivity may be caused by cockpit automation. Related concerns include the potential for automation to reduce crew alertness or cause them to be easily distracted.[13] Certain recent airline accidents are interpreted to have been automation-induced and they may be preventable in the future by putting the human "into a more active role in the control loop".[14] Pilot-astronauts and spacecraft are analogous to airline pilots and aircraft and this workload level concern is relevant to space operations as well. Research has shown that tasks containing relatively long periods of inactivity are perceived as being high in workload.[1] Both too many and too few inputs required per unit time are potentially hazardous. Minimizing workload by mandating a slow approach velocity is not necessarily the safest approach.

Maintaining slow vehicle velocities serves to lengthen the safe range of human reaction time and reduce the likelihood of frenzied activity which may tend toward the instigation of (potentially tragic) errors. This is one of the reasons for speed limits on the nation's highways and is also why roads are not designed with a large number of tight, contiguous S-curves, which increase workload. However, too slow velocities may lead to long periods of inactivity which also may increase the incidence of accidents. To make use of the highway analogy again, curves are installed not only around obstacles but also at appropriate intervals to "awaken" the drivers whose attention may have lapsed due to the relatively mindless piloting of an automobile down a straight road for too long. In short, both too many and too few inputs required per unit time are potentially hazardous. Again, minimizing workload is not necessarily the safest approach.

Little rigorous human factors testing has been conducted to date in the area of spacecraft docking maneuvers. It has routinely been assumed that in spaceflight--and other activities requiring manual control--that the human is such a marvelous machine that it can adapt to any operational environment. With the awareness of the aforementioned concerns of error incidence, time and productivity issues, and cost, it is time to perform some experiments with which to better understand these considerations in the hopes of alleviating or minimizing potential problems.

The author has been involved with human factors investigations of proximity operations for a number of years. Previous work in a spacecraft flight simulator with naive test subjects yielded remarkable results concerning the ability to dock a manned OMV to the space station. While NASA policy stipulates the requirement of 1,000 hours of high performance jet pilot experience for its pilots, none of the author's test subjects had any jet pilot experience. Nevertheless, successful dockings were achieved in less than 4% of the time that would have been obtained had the 0.1% rule been followed. Mission costs were cut substantially as well. In essence, students without the benefit of jet pilot experience or (except for one subject) any kind of flight training, instruction in orbital mechanics effects (except for another subject), or any form of NASA

training, achieved a high success rate "speeding" toward the space station in simulated dockings. Indeed, one simulator study claims that almost anyone can perform a successful docking maneuver with great precision with documented cases including data from secretaries and experienced pilots.[8]

This study was a partial replication of the earlier one.[2] While the two studies were similar in that they both sought to examine the effect of different docking velocities on failure rate, fuel consumption, and mission duration, there were enough fundamental differences in methodology, hardware, and software to justify a new study. These differences include the addition of an accurate star field in the background of the current study, a different thruster control system, different environments, different computers and displays, and different points of view. (The earlier study consisted of a pilot flying his craft toward the station while the current study involves remotely controlled docking.)

EXPERIMENTAL METHODS AND APPARATUS

This experiment was conducted in the Space Station Proximity Operations (PROX OPS) Simulator at NASA/Ames Research Center. The simulator primarily consists of one 3-degree-of-freedom hand controller and three "windows" on which the computer-generated imagery is presented. Buttons on the hand controller are used to select the thruster acceleration values for each axis among choices of 0.01, 0.1 and 1.0 m/s. Detailed descriptions of the simulator are available elsewhere.[4,5,6,7]

Test subjects were required to "fly" simulated remote docking maneuvers of an OMV to a space station in a 270 nautical mile orbit beginning from an initial range of 304.8 m (1,000 ft) on the -V-bar (along the velocity vector in the minus direction). A repeated measures design was used with ten missions flown at each of five initial velocities: 0.3, 3.0, 5.0, 7.0, and 9.0 m/s. From this direction, orbital mechanics effects cause the vehicle to rise. The subjects were instructed to counteract this tendency by making downward burns to accomplish a successful docking. The order that these velocities were presented was randomized and was different for each subject. Subjects were requested to resist boredom at the slowest velocity and were prohibited from accelerating to decrease the mission duration. In addition, each subject also performed ten attempts without the benefit of operational range and rate displays. These trials were performed last (at an initial velocity of 3 m/s) as they were presumed to be the most difficult and the trials with the displays would serve as practice.

Each subject was issued a training manual for perusal prior to experimentation. Training consisted of performing ten successful dockings with an initial velocity of 3.0 m/s. Once ten successful dockings were achieved, training was considered complete and data collection began.

Certain range and rate conditions had to be satisfied for a docking attempt to be considered successful. These were: a forward range of 2.0 m with an approach velocity no greater than 0.15 m/s, and up/down and left/right ranges and rates with absolute values that did not exceed 0.23 m and 0.06 m/s respectively. These values were derived from the proceedings of a NASA workshop on rendezvous and docking and were believed to be the most recent.[11]

## RESULTS

Eight male subjects were tested for approximately six hours each. Time considerations prevented some of the subjects from completing all ten of the runs at 0.3 m/s but no subject performed fewer than eight. Qualitative data in the form of comments by the subjects in addition to quantitative data concerning mission duration, fuel consumption, and error incidence were recorded. Only one of the subjects had previous pilot experience (subject three).

The values for per cent unsuccessful were determined by dividing the number of failed missions for each subject by the number attempted and multiplying by 100. These values were then summed which is why the total sometimes exceeded 100%. (See Figure 1.) While most of the unsuccessful missions were not tragic in nature, for experimental purposes, "unsuccessful" was operationally defined as not satisfying the terminal range and rate conditions mentioned earlier.
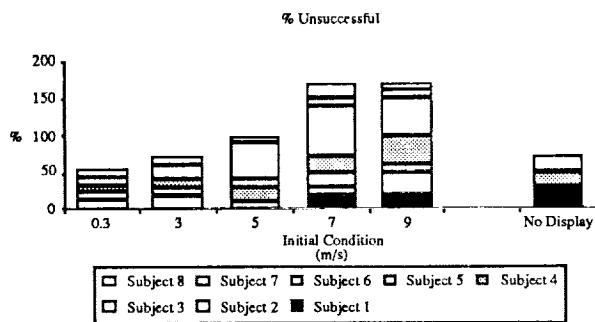


Figure 1--Per Cent Unsuccessful by Initial Condition

The data were analyzed across initial conditions and across subjects. By initial condition, the values for per cent unsuccessful ranged from 6.70% (5 "accidents") at 0.3 m/s to 21.25% (17 unsuccessful) at both 7 and 9 m/s. The corresponding values by subject were 1.68% (1 failure) for Subject 8 to 30.0% (18 failures) for Subject 5. The average failure rate by subject or initial condition was 13.2%. A two-way analysis of variance (ANOVA) was performed on these data with subject and initial condition (velocity) as factors. Only the between subject data were significant with an F-ratio of F(7,35)=3.38 (p=.007).

Median scores for mission duration and total impulse were plotted as functions of initial condition. The units for these measurements are seconds (s), and meters per second (m/s). Meters per second are the units for $\Delta v$ which is the change in velocity imparted to the vehicle. By using the total impulse as the value for fuel usage, the mass of the vehicle becomes immaterial and the fuel consumption can be scaled for a vehicle of any mass. These data appear in figures 2-3.
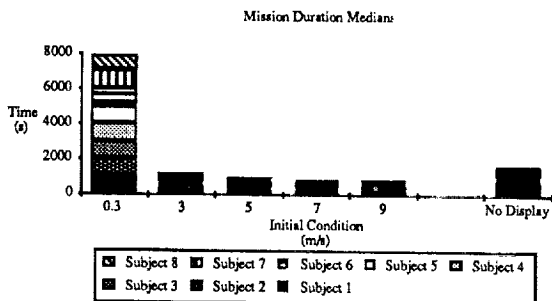


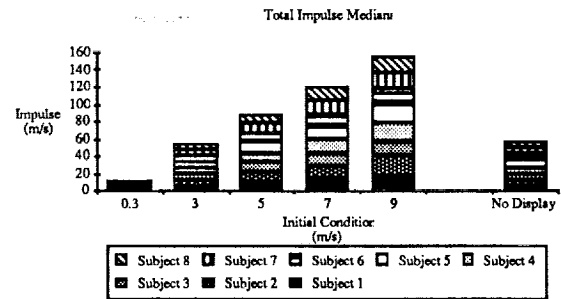Figure 2--Mission Duration Medians by Initial Condition



Figure 3--Total Impulse Medians by Initial Condition

Since mission duration and total impulse were heavily influenced by the initial velocity of the vehicle, the data for these parameters are more important for mission operations considerations than for human performance analyses. Consequently, mission duration and total impulse were "normalized" by subtracting out appropriate reference values. The reference value for mission duration was computed by dividing the initial range by the initial velocity. This provides a theoretical minimum time for a linear, one-dimensional system (which does not characterize the orbital environment) with impulsive start and stop. The parameter thus obtained is termed "reserve time" as this is the time the subject reserves for himself in order to successfully dock.

In a similar fashion, the starting impulse and the impulses used to decelerate the vehicle were subtracted from the total impulse to arrive at the value used to maintain the OMV near the V-bar. (Since the OMV rarely came to a full stop, the vehicle was assumed to have a residual velocity of 0.1 m/s for this calculation.) This derived parameter was termed "radial impulse" as this was the sum of the radial impulses used to achieve a successful docking.

Reserve time medians averaged over all subjects ranged from a low of -22.2 s at 0.3 m/s to a high of 108.4 s with the No Display trials. (A negative reserve time was caused by reducing the altitude of the OMV for so long that its orbital period was significantly shorter from that of the station and it gained some forward velocity.) Across treatments, the averages ranged from 23.8 s (Subject 4) to 114 s (Subject 1). For the reserve time medians, the omnibus F test produced ratios of F(5,35)=6.73 (p<.001) and F(7,35)=2.23 (p=.055) for the between treatment and between subject data respectively. (See Figure 4.)
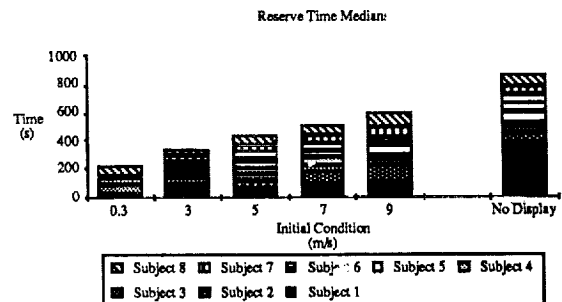


Figure 4--Reserve Time Medians by Initial Condition

The F-ratios for radial impulse medians were F(5,35)=2.81 (p=.031) and F(7,35)=6.68 (p<.001) for between treatment and between subject analyses. Averages of medians across subjects ranged from 1.02 m/s at 0.3 m/s to 1.77 m/s at 9

m/s. Across treatments, the values varied from 0.75 m/s for subject three to 2.1 m/s for subject five with an average of 1.26 m/s. (See Figure 5.)
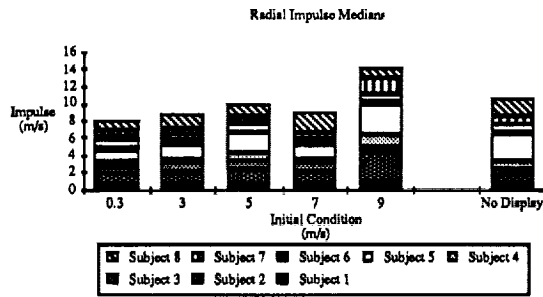
Radial Impulse Medians



Figure 5--Radial Impulse Medians by Initial Condition

Two-way ANOVAs were also conducted for the three parameters using only the 3 m/s and No Display (also 3 m/s) medians to determine the effect of the removal of the displays. None of these F ratios proved significant.

DISCUSSION--ANALYSIS

Before discussing the results in any detail, it must be emphasized that none of the subjects had any background or experience with orbital mechanics effects or any high performance jet flight training. The data show how well naive subjects can do without either of these skills. Also, none of the pilots had access to any orbital trajectory planning device to assist them with their docking missions. (This is being planned for a future study.) It is expected that NASA pilots with these skills, and more, could easily surpass the best mission duration, fuel consumption, and success rate values achieved here. Subjects and NASA pilots alike can be trained to virtually any desired design point for any, or all, of the three parameters before they are considered competent to perform an actual docking.

The qualitative comments clearly indicated extreme dislike for the trials at the slowest velocity and preference for any of the other treatments, especially the runs without the range and rate displays. However, the anxiety associated with the performance of an actual space mission may alleviate some of the boredom and help time "fly".

The data obtained for the unsuccessful missions, categorized by initial condition and by test subject, show that while the incidence of accidents appears to increase with initial velocity, this trend was not statistically significant. Only the subject effect was significant. Subjects had different risk profiles; some were risk prone and some were risk averse. In actuality, docking velocities would not be chosen because of their associated success rate in simulations. Rather, the pilots would be chosen by their established success rate in simulated maneuvers. Unlike other vehicles such as aircraft or automobiles where the landing scheme or speed limit must be designed to safely accommodate the worst pilots (drivers), for spacecraft and space missions, "the simulator defines the user population rather than vice versa." A velocity would not be selected because it induced the lowest failure rate averaged over all subjects, rather, those who performed the best in the simulated mission would be chosen to perform the actual mission.[4]

The analysis of variance performed on reserve time medians showed that reserve time increased with initial velocity without any statistical significance among test subjects. While mission duration varied inversely with initial velocity, reserve time increased monotonically with initial velocity with the no display runs performed at 3 m/s requiring more reserve time than the runs at 9 m/s. This effect was mostly due to the equations of motion governing orbital flight. By traveling at a different altitude from the station, forward velocity was obtained without the use of fuel. During the longer (slower) missions, orbital mechanics effects had more time to work to the subjects' advantage allowing more velocity to be accumulated and consequently reducing the time the pilot reserved to successfully accomplish the mission.

The radial impulse data were significant both by subject and by treatment. This indicates that not only were different amounts of fuel required to compensate for a non-linear environment depending upon the initial velocity, but that some subjects were significantly more fuel efficient than others when it came to applying these radial burns.

The fact that removal of the range and rate displays at 3 m/s did not significantly affect the data for any of the parameters is very important. This indicates that such displays, while probably psychologically comforting, were redundant in a real-life situation when combined with the visual image of the approaching vehicle and were unnecessary for nominal dockings. They did not help the test subjects perform more rapid, more fuel efficient, or safer dockings. They would most likely be more useful in anomalous situations. These range and rate data would be produced by a sophisticated and expensive ranging system which the current space shuttle does not possess and it is deemed too expensive to retrofit the shuttle to include it. This lends support to the view that installing such a system on the shuttle is not worth the time, money, or effort since these displays apparently do not produce any significant benefit in simulated nominal missions. The OMV is expected to have such a ranging system (which is one of the reasons it was used as the test vehicle in this study) and these data would be required for an automatic system to function as well.

CONCLUSIONS

• The amount of time pilots reserved for final approach increased with starting velocity. The slower forward velocities allowed more time for the orbital mechanics effects to play a role and were thus used to the pilot's advantage in gaining forward velocity for free.
• Performance of simulated remote piloting of docking maneuvers was not significantly affected in any way by the removal of the range and rate displays.
• The initial condition significantly affected the subjects' use of reserve time and radial impulse.
• The "0.1% Rule" for docking is overly conservative from a human performance point of view.

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