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# Modifications to the NASA Ames Space Station Proximity Operations (PROX OPS) Simulator

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# Modifications to the NASA Ames Space Station Proximity Operations (PROX OPS) Simulator

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## Symbols and Abbreviations

| | |
|---|---|
| a | semi-major axis of elliptical orbit |
| DAP | digital auto pilot |
| DOF | degree(s) of freedom |
| HUD | head-up display |
| LEO | low earth orbit |
| m | meters |
| m/s | meters per second |
| n | mean orbital motion, average angular velocity in radians per second |
| OMV | orbital maneuvering vehicle |
| n mi | nautical mile |
| P | orbital period |
| PROX OPS | proximity operations, those operations occurring within a 1 kilometer sphere of the space station |
| t | time |
| V-bar | the velocity vector |
| $V_x$ | velocity in the x direction |
| $V_y$ | velocity in the y direction |
| $V_z$ | velocity in the z direction |
| X | radially outward |
| Y | along the positive velocity vector |
| Z | out of plane to the left |
| $\Delta v$ | change in velocity imparted to a space vehicle |
| $\mu$ | gravitational constant |

## Summary

The Space Station Proximity Operations Simulator at NASA Ames Research Center was modified to provide the capability for investigations into human performance aspects of proximity operations. Accurate flight equations of motion were installed to provide the appropriate visual scene to test subjects performing simulated missions. Also, the flight control system was enhanced by enabling pilot control over thruster acceleration values. Currently, research is underway to examine human performance in a variety of mission scenarios.

## Introduction

Flight simulators have been an important part of pilot training since the original Link Flight trainer was used in the 1940s. They have been incorporated into the United States space program since Project Mercury and while they were initially developed for training purposes, they are now heavily utilized for engineering, operations, and human factors research. As the U. S. is approaching an operational space station era, flight simulators are required to investigate human design and performance aspects associated with orbital operations. Among these are proximity operations (PROX OPS), those activities occurring within a 1 kilometer sphere of the space station including rendezvous, docking, rescue, and repair.

The Proximity Operations Simulator in building 239A at NASA Ames Research Center was built to allow researchers to explore and demonstrate the potential for, and value of, developing engineering design guidelines in a number of human factors areas such as: workload assessment, external vision envelope requirements, head-up and head-down symbology development, and use of voice synthesis and recognition and expert automation systems. Two orbital maneuvering vehicles (OMVs) and one space shuttle orbiter were independently controllable in six degrees of freedom (DOF) with one three DOF hand controller. However, human factors aspects of pilot performance during simulated maneuvers were never explored. Detailed descriptions of the basic hardware and software construction are available elsewhere. [Haines, 1987, Lee & Wu, 1987]

The author has modified the software to provide a much more accurate representation of spacecraft flight in the low earth orbit (LEO) environment. A functional space station simulator now exists which is capable of supporting research dedicated toward investigating human factors issues associated with PROX OPS and other orbital operations. What follows are the details of the software upgrades made to effect a better semblance of realism. Most of the algorithms were adapted from those developed by the author in the Laboratory of Orbital Productivity section of the Space Systems Laboratory at the Massachusetts Institute of Technology. [Brody, 1987]

Orbital Mechanics

One of the most important sections of computer code associated with any flight simulator are those dictating the governing equations of motion for the vehicle(s). In this case, the equations which govern the relative motion between one orbiting body (such as an OMV) and another in a circular orbit (like a space station) are collectively known as the Clohessy-Wiltshire solutions to Hill's equations. With X measured radially outward, Y along the positive velocity vector and Z positive out of the orbital plane to the left, the closed forms for position are:

$$X = \frac{V_{x0}}{n}\sin(nt) - (2\frac{V_{y0}}{n} + 3X_0)\cos(nt) + 2\frac{V_{y0}}{n} + 4X_0$$

$$Y = 2\frac{V_{x0}}{n}\cos(nt) + (4\frac{V_{y0}}{n} + 6X_0)\sin(nt) + (Y_0 - 2\frac{V_{x0}}{n}) - (3V_{y0} + 6nX_0)t$$

$$Z = Z_0\cos(nt) + \frac{V_{z0}}{n}\sin(nt)$$

The mean orbital motion, n, equals:

$$\sqrt{\frac{\mu}{a^3}}$$

where a is the semi-major axis of the elliptical orbit and $\mu$ is the gravitational constant equal to 398604 $km^3/s^2$ for the earth. To compute the orbital period, the formula:

$$P = 2\pi\sqrt{\frac{a^3}{\mu}}$$

is used. [Kaplan, 1976] For a 270 n mi orbit around the earth, like the space station's, the period is 94.6 minutes. The time derivative of each of these equations yields the corresponding velocity equations:

$$V_x = V_{x0}\cos(nt) + (2V_{y0} + 3nX_0)\sin(nt)$$

$$V_y = -2V_{x0}\sin(nt) + (4V_{y0} + 6nX_0)\cos(nt) - (3V_{y0} + 6nX_0)$$

$$V_z = -Z_0 n\sin(nt) + V_{z0}\cos(nt)$$

A vehicle's orbit is determined by its altitude and velocity components after thrust is applied. The time parameter in the above equations is reset to 0 after every burn to calculate the resulting trajectory. Likewise, the initial conditions, $X_0$, $Y_0$, $Z_0$, $Vx_0$, $Vy_0$, and $Vz_0$ are set to whatever values they happen to be when t = 0. A separate "clock" is maintained for each vehicle to enable completely independent motions. In this way, one vehicle's burn will not reset the initial conditions of the other vehicles and the three vehicles may be manipulated concurrently and separately.

Flight Control System

Previous research revealed the necessity for variable thrust engines for vehicles to be able to successfully dock to the space station. It was very difficult (or impossible) to achieve the sensitivity and fine tuning required for close in maneuvers requiring velocity changes, $\Delta$vs, on the order of 0.01 m/s with an engine which provided an acceleration of 1 m/s/s. Conversely, at target-chaser ranges of several hundred meters or more, where burns producing $\Delta$vs on the order of 1 m/s are desired, firing a thruster yielding an acceleration of 0.01 m/s/s for 100 seconds to achieve the desired thrust is impractical. [Brody, 1987] A pilot on the Space Shuttle Orbiter uses a digital auto pilot (DAP) to select the thrust values for each axis. This is accomplished at Ames with the three buttons on the hand controller.

Each button toggles among 1.0, 0.1, and 0.01 $m/s^2$ for each translational axis. Previous experimentation suggested the use of these discrete values. [Brody, 1987] Generally, the faster rates are used at greater distances with the acceleration values decreasing with range. The acceleration values are displayed on the head-up display (HUD) on the center window. With a value of 1.0 selected, the velocity of the selected vehicle will increase by one meter per second every second in the direction in which the hand controller is displaced. Without the ability to vary the acceleration, both fine and coarse adjustments in the flight path are impossible and many overshoots generally result.

Head-Up Display

The existing HUD was modified to provide to the pilot the information generated by the other software modifications. Range and range rate displays for each axis were added to give the pilot a better situational awareness than was possible with just slant range and slant range rate displays. The space station body coordinate system is used with +X along the +V-bar in the direction of station motion, +Y to the right when facing forward, and +Z downward. [NASA Johnson, 1986] From the operator's point of view, forward is -X, starboard (right) is -Y, and upward is -Z. The slant range and slant range rate displays were kept, however, for those operators who would appreciate absolute distance and velocity values. Additionally, for experiments involving two vehicles besides the space station, the slant range/rate displays can be used to indicate absolute values between the other bodies. The crew optical alignment sight (COAS) reticule was also kept but is now always present on the screen rather than as an operator option.

Time and delta-v ($\Delta v$) displays were installed at the top of the screen. The displayed time can either be mission elapsed time or time since last burn, with units in seconds. The units for $\Delta v$ are m/s. (See Figure 1.)

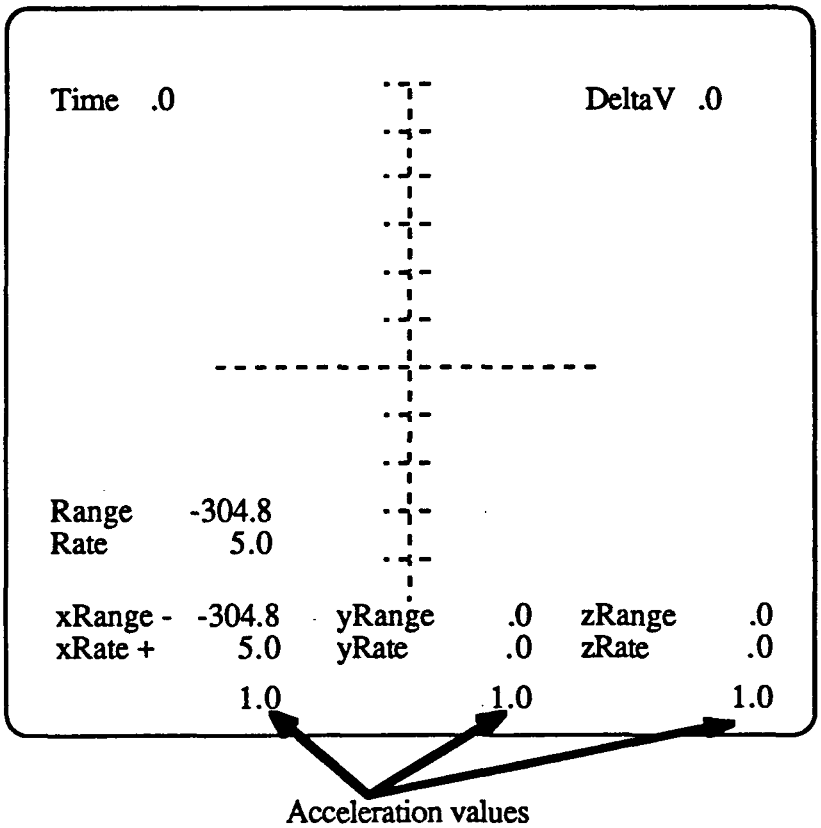


Figure 1--Head-Up Display

The physical 3-axis range and range rate requirements for a successful docking to the space station will be very strict. The most recent specifications dictate that axial (X) velocity must be between 0.05 and 0.15 meters per second inclusive, absolute Y and absolute Z velocities must be no greater than 0.06 m/s and the maximum allowable angular velocity is 0.6 degrees per second. The Y and Z misalignments are limited to 0.23 m and angular deviations should not exceed 5.0 degrees of roll or 6.0 degrees of pitch or yaw. [NASA Johnson, 1985] After each mission, a monitor on the control panel indicates whether the mission was successful and what the final range and rate values were upon docking. For unsuccessful missions, the faulty value is highlighted.

To relieve the pilot from the need to memorize the final docking requirements, plus and minus signs were added to the display as cues. These cues appear immediately after each range and rate title (except for slant range and slant range rate) and indicate if the pilot is erring and in which direction(s). The ultimate goal is to eliminate all cues (except that for xRange) from the screen by the time the spacecraft reaches a docking range of -2.0 meters in the X direction. These cues are not meant to serve as a flight path guide but merely as indications of whether final docking conditions are being met.

## Current and Future Work

Many studies are possible now that an operational simulator is available. One experiment was designed to determine the effect of initial velocity on the ability of a pilot to dock an OMV to the space station from a stable offset point on the -V-bar. Another is designed to investigate human factors aspects of docking with objects that are moving with respect to the space station. Further studies will explore: the effect of docking port location on docking, the impact of orbital trajectory planning tools on rendezvous and docking, new HUD symbologies, various acceleration values and docking profiles, dockings from other than stable offset points, etc. The hope is to develop a unified theory of human factors aspects of rendezvous and docking in LEO and then extrapolate to make inferences about orbiting moon and Mars stations.

References

Brody, Adam Randall. 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, S. M. Thesis, Massachusetts Institute of Technology, April, 1987.

Haines, Richard F. Space Vehicle Approach Velocity Judgements Under Simulated Visual Space Conditions, NASA TM 89437, August 1987.

Kaplan, Marshall H. Modern Spacecraft Dynamics & Control. New York: John Wiley Sons, 1976.

Lee, E. and A. Wu. Space Station Proximity Operations Workstation Docking Simulation, Sterling Software NM 7104-519-13, 1987.

NASA Lyndon B. Johnson Space Center, *Proceedings of the* Rendezvous and Proximity Operations Workshop, 1985.

NASA Lyndon B. Johnson Space Center, *Space Station Program Office*, Space Station Reference Coordinate Systems, JSC 30219, 1986.

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16. Abstract


As the United States is approaching an operational space station era, flight simulators are required to investigate human design and performance aspects associated with orbital operations. Among these are proximity operations (PROX OPS), those activities occurring within a 1 kilometer sphere of the space station including rendezvous, docking, rescue, and repair. The Space Station Proximity Operations Simulator at NASA Ames Research Center was modified to provide the capability for investigations into human performance aspects of proximity operations. Accurate flight equations of motion were installed to provide the appropriate visual scene to test subjects performing simulated missions. Also, the flight control system was enhanced by enabling pilot control over thruster acceleration values. Currently, research is underway to examine human performance in a variety of mission scenarios.


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