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Handling Qualities Evaluation for Spacecraft Docking in Low Earth Orbit

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A new generation of spacecraft is now under development by NASA to replace the Space Shuttle and return astronauts to the Moon. These spacecraft will have a manual control capability for several mission tasks, and the ease and precision with which pilots can execute these tasks will have an important effect on mission risk and training costs. A simulation evaluated the handling qualities of a generic space vehicle based on dynamics similar to one of these spacecraft, NASA's Crew Exploration Vehicle, during the last segment of the docking task with a space station. This handling qualities evaluation looked at four different translational control systems, two of which are available in current space vehicles and two of which were adapted from aeronautical vehicle control system designs. These response types were flown with three levels of translation-into-rotation dynamic coupling arising from a longitudinal offset between the reaction control system thrusters and the vehicle's center of mass. The effect of variations in jet thrust was also measured for a single response type. The results indicate that greater translation-into-rotation coupling is strongly correlated with degraded handling qualities, but that different response types do not have a major effect on pilot workload, final docking performance, or overall handling qualities.

I. Introduction

Handling qualities are those characteristics of a flight vehicle that govern the ease and precision with which a pilot is able to perform a flying task.[1] Several factors impact a pilot's perception of the handling qualities and in turn affect a vehicle's ability to accomplish a desired mission. These factors include the stability and control characteristics of the unaugmented vehicle, the control systems that enhance these characteristics, the inceptors (e.g., stick or throttle lever) used by the pilot to transmit control commands, and the cues that provide flight information to the pilot. Cues that assist the pilot in the execution of the flying task may be visual (the displays, instrumentation, guidance and out-the-window view) proprioceptive, or aural. The effects of the above factors on handling qualities have been studied in atmospheric flight vehicles for over seventy years.[1–4] Reference standards for the handling qualities of both fixed-wing aircraft[5] and rotary-wing aircraft[6] have been developed, and are now in common use. Broadly speaking, these standards define a subset of the dynamics/control design space that provides good handling qualities for a given vehicle type and flying task. For example, the standards may specify a range of combinations of damping and natural frequency for a large aircraft during landing that corresponds with acceptable and unacceptable handling qualities.

At this time, no reference standards exist for handling qualities of piloted spacecraft. Handling qualities have been assessed for some space vehicles;[7–9] however, the focus of these studies was to evaluate and/or address deficiencies in the handling qualities of an existing point design for a specific vehicle. A more systematic approach would map out handling qualities variations over a broad range of design variables to determine desirable regions in the design space for a class of vehicles.

NASA and private commercial interests are designing a new generation of piloted spacecraft.[10] These vehicles include the Crew Exploration Vehicle (CEV, also known as Orion) to replace the Space Shuttle and ferry astronauts to lunar orbit, and the Altair spacecraft to provide transportation to and from the lunar surface. The ability of pilots

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to successfully carry out their missions will be determined in part by the handling qualities of these new spacecraft. Some operational tasks may be fully automated, while other tasks are executed with a human pilot fully engaged in the control loop. Even for the nominally automated tasks, NASA requires a backup manual control capability so that a human pilot may take over when an automated system or critical sub-component of the spacecraft fails. In these cases of emergency reversion to manual control, where the pilot role abruptly switches from monitoring to active control, it is even more important that the vehicle have good handling qualities. It is, therefore, desirable for spacecraft designers to assess early in the design cycle what the handling qualities will likely be, and to adjust their design if necessary to ensure that adequate handling qualities are preserved even in degraded or failed operational modes.

An effort to develop design guidelines for spacecraft handling qualities was initiated by NASA in 2007. A comprehensive set of guidelines should cover all classes of spacecraft and phases of flight; however, near-term NASA program goals make it necessary to focus initially on a few specific and relevant aspects. This paper reports an experiment investigating the docking of two spacecraft in low Earth orbit; specifically, the effect of translation-into-rotation coupling, response type design and control power on handling qualities is evaluated. Companion papers report on experiments investigating the final approach and touchdown phase of lunar landing,[11] and a six degree-of-freedom piloting task for docking with a space station.[12]

II. Experiment Design

The principal objective of the experiment was to map out variations in handling qualities for various combinations of translational control response types and Reaction Control System (RCS) thruster ring locations relative to the vehicle's center of mass (c.m.). The task selected was the final stage of docking operations during which the visiting vehicle, in this case modeled on the Crew Exploration Vehicle (CEV), approached the International Space Station (ISS) along its velocity vector (this is known as the V-bar approach). This approach is done today with the attitude hold system engaged; the pilot need only control the lateral motion of the vehicle to close out errors in relative alignment and monitor the closure rate. The pilots in this simulation were similarly tasked with controlling those two degrees of freedom in translation. The motion of both vehicles was modeled, including primary orbital mechanics effects, using the flight dynamics model described in Section III. In this simulation, the ISS was in a circular orbit 350 km above the surface of the Earth, with no perturbations in position or attitude during the task. The simulation model was implemented on the NASA Ames Vertical Motion Simulator (VMS), and a piloted evaluation of docking handling qualities was conducted in October and November 2007. Ten current or retired pilot astronauts and four NASA test pilots served as evaluation pilots for the experiment. Pilots provided Cooper-Harper ratings,[1] NASA Task Load Index (TLX) ratings,[17] and qualitative comments. The fourteen

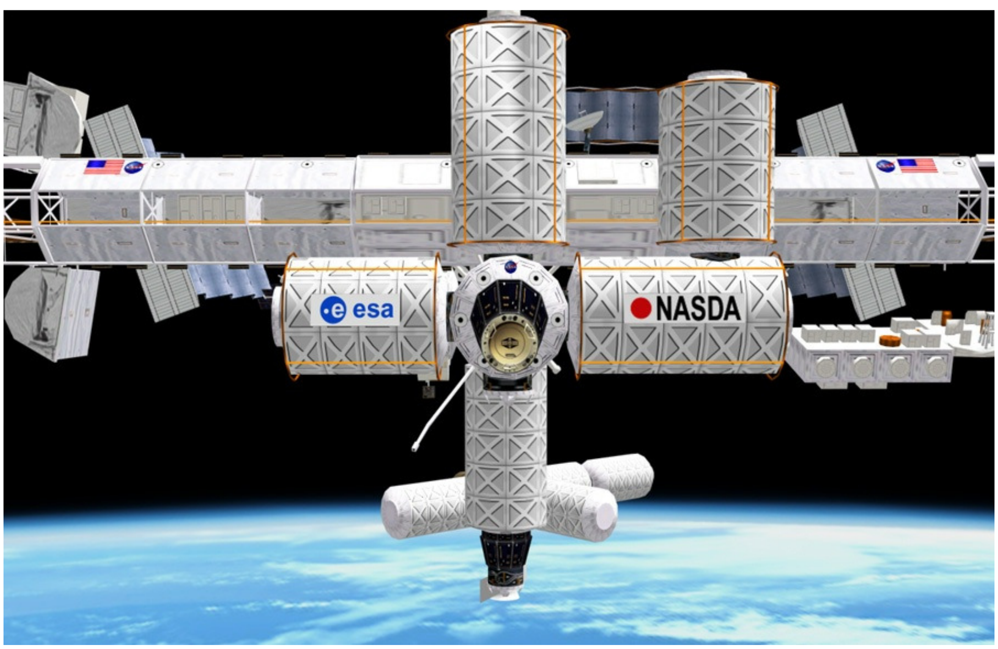

Figure 1. View pilots would see out the window at approximately 100 ft from docking.

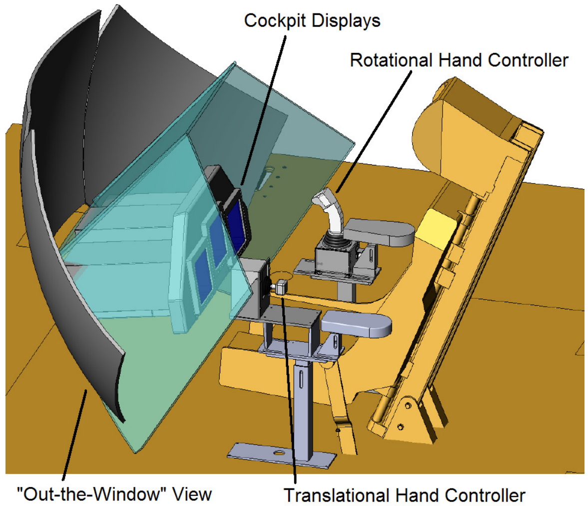

Figure 2. Cockpit layout in the VMS cab.

pilots have an average of 7500 hours in aircraft and rotorcraft, and the ten pilot astronauts have flown a total of 14 Space Shuttle missions as Pilot and 11 missions as Commander.

A. Initial Conditions

At the start of the simulation run, the axial distance between the CEV and ISS docking ports is 10 ft and the relative axial closing speed is 0.1 fps, resulting in a nominal run time of 100 sec. There is no error in CEV attitude and angular rates relative to the ISS. In order to provide sufficient piloting challenge and expose any handling qualities issues, a significant radial offset of 4.2 ft was applied to the initial condition. This resulted in four initial positions of the CEV relative the ISS, on the corners of a square centered on the ISS docking port. One of these initial positions - always below and left of the docking port - was utilized for training and familiarization runs, while the other three were used for data collection runs.

B. Cockpit Layout

A single pilot seat was installed in the center of the simulator cab, with a researcher/observer seat immediately aft of the pilot seat. The out-the-window view showed the ISS approximately as it would appear from the left (commander's) seat of the CEV. A three-axis rotational hand controller (RHC) was installed on the right side of the pilot seat, and a three-axis translational hand controller (THC) was installed on the left side of the pilot seat. A view the pilot would see out the window of the vehicle at a distance of about 100 ft is shown in Figure 1; note that this distance is farther than the pilots would ever be from docking during data collection runs. A schematic of the cockpit layout including the two controllers is shown in Figure 2.

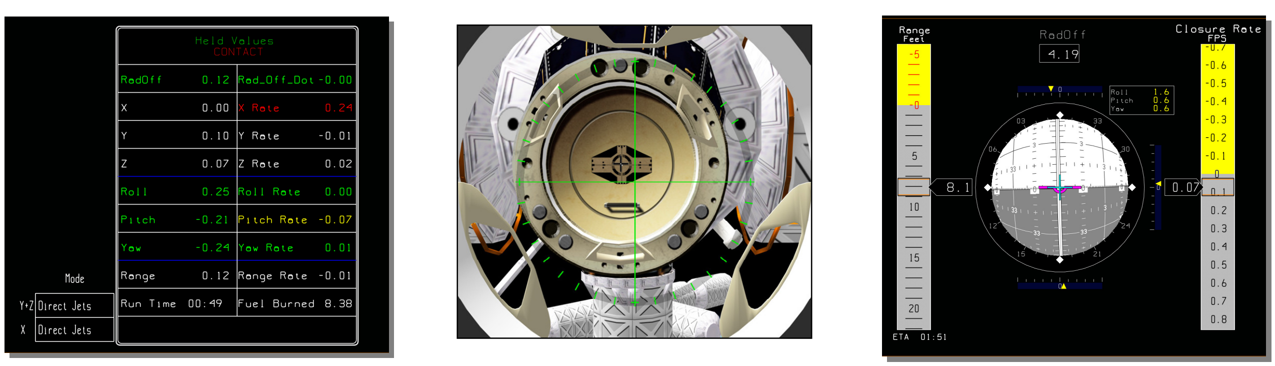

Figure 3. Cockpit displays.

The panel in front of the pilot seat had three 6.5-inch color flat panel displays, the contents of which may be seen in Figure 3. The right panel displayed an Attitude Direction Indicator (ADI) and also included tapes showing range

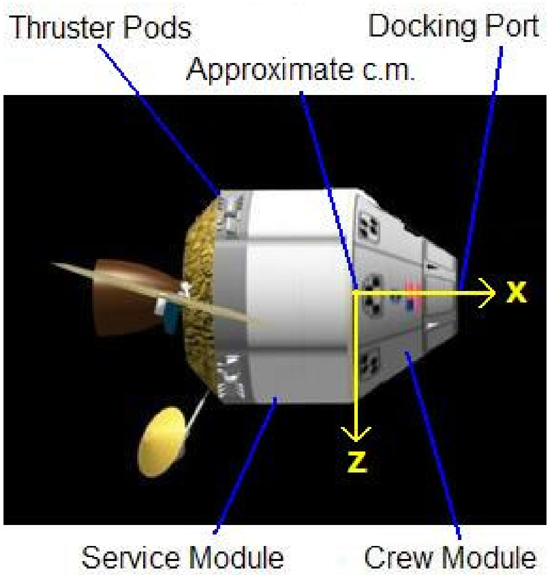

Figure 4. Side view of CEV with body-axis coordinate system.

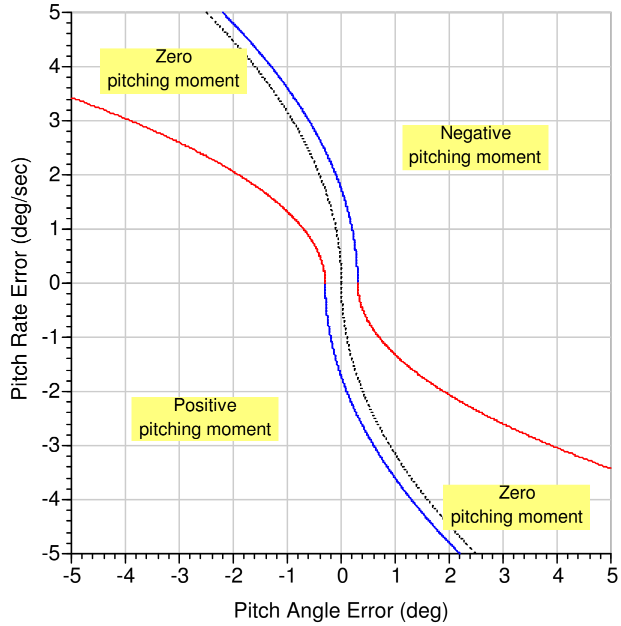

Figure 5. Switching curves (red and blue) for the attitude hold control system - example is for the pitch axis.

and range-rate of the CEV's docking port relative to the center of the ISS' docking port. The center panel displayed a simulated view from a camera mounted on the centerline of the CEV dock, overlaid with a green reticle (cross-hairs). The ISS dock is the beige ring with numerous holes and three petal-like objects in the center of this display. The left panel displayed streaming data of key docking parameters, such as radial offset error and relative angular rates.

C. CEV Model

Generic vehicle dynamics and control systems for translation and attitude were developed for this experiment using the most recent CEV configuration information available at the time (early autumn, 2007). That design information included the Reaction Control System (RCS) thruster locations, vehicle dimensions, mass properties and other pertinent details, but did not include control system details; control system designs representative of a range of possible implementations were developed for this experiment. A side view of the CEV showing the body axis coordinate system and important subsystems is provided in Figure 4. The following response types were provided in the translation axes:

1. Single Pulse Jets (SPJ): displacement of the inceptor out of detent commands the appropriate RCS thrusters to fire for a specific duration, resulting in a fixed velocity increment (0.01 fps); the inceptor must be returned to detent before another command can be issued. This response type is similar to that used by the Space Shuttle today and is currently the response type planned for the CEV.
2. Continuous Jets (CJ): displacement of the inceptor out of detent commands the appropriate RCS thrusters to fire until the inceptor is returned to detent.
3. Proportional Translational Rate Command / Position Hold (TRC/PH): displacement of the inceptor out of detent commands a translational velocity proportional to the inceptor displacement, up to a maximum of 0.2 fps; returning the inceptor to detent captures the spacecraft position relative to the docking target, and fires thrusters as required to capture and hold that position within a 0.06 ft deadband. The velocity deadband when in translation rate command mode is 0.01 fps. The captured position is the position of the vehicle center of mass (c.m.) when the inceptor is placed back in detent.
4. Discrete Translational Rate Command / Position Hold (TRC/PH): same as Proportional TRC/PH above, except that the translational velocity command is always 0.1 fps when the inceptor is out of detent.

While a similar set of response types were developed and available in the rotational axes, only a single response type was used in this experiment:

Proportional Rate Command / Attitude Hold (RCAH): displacement of the inceptor out of detent commands the RCS thrusters to fire to achieve an angular rate proportional to the inceptor displacement;

Response Type → / Thrust Coupling ↓	Continuous Jets	Single Pulse Jets	Proportional TRC/PH	Discrete TRC/PH
Zero				
Low (50%)				
Baseline (100%)			Control Power Study 50%, 150%, 200%	

Figure 6. Experiment matrix.

returning the inceptor to detent captures the spacecraft attitude, and fires thrusters as required to maintain that attitude within a deadband of 0.25 deg.

For the closed-loop control laws, both translational and rotational, phase-plane implementations based on the time-optimal (parabolic) switching curves were used to hold position and attitude (see Figure 5). In that figure, the time-optimal switching curve is shown as a dotted black line and the red and blue lines surrounding it represent the edges of the deadband within which the RCS thrusters do not fire. The blue lines have precisely the same shape as the time-optimal curve, but the red lines bend steeply towards the angular error axis in order to limit the angular rate at which the vehicle traverses the deadband. In essence, the degree of bending of the red lines represents a tradeoff between propellant use and the time it takes to remove errors.

An important aspect of the vehicle's dynamics is the degree of coupling from translational inputs into rotational motions. This dynamic coupling arises from the offset between the RCS thruster ring and the vehicle center of mass (c.m.), and results in a thrust coupling between translational and rotational motion that can have a significant impact on handling qualities. For example, an RCS force acting to push the vehicle to the left will indeed move the vehicle c.m. to the left immediately, but will also induce an unwanted yawing moment that moves the vehicle's nose to the right. Since the centerline camera is mounted on the nose of the CEV and shows the net motion of the nose (caused by both translation and rotation effects), the pilot may perceive a motion in the "wrong" direction until the attitude hold system engages and takes out the yawing moment.

The thrust model of the vehicle was obtained by calculating the resultant forces and moments arising from a pure command in a single axis. For pitch, roll or yaw commands the only moments were about the pitch, roll or yaw axis; however, as discussed above for the translation-into-attitude coupling, a pure translation command resulted in a corresponding rotation about one or more axes. These forces and moments were imparted whenever a translation or rotation command was received, whether it originated from the pilot or any of the rate command or position/attitude hold systems. This implementation allowed forces and moments to be generated in any and all axes at once; however, in practice such an unrealistic confluence of commands was never observed.

D. Experiment Matrix

A schematic of the primary experiment matrix is shown in Figure 6. Pilots were presented three different values of coupling, ranging from zero to the baseline for the CEV, for a single response type before moving on to a different response type, and the order in which these conditions were given to each pilot was systematically varied to preclude learning effects from contaminating the results.

A secondary objective of the experiment was to determine variations in docking handling qualities for various values of control power, i.e., the thrust produced by each RCS jet. This was done for the configuration of Proportional TRC/PH response type and baseline thrust coupling. The control powers evaluated were 50%, 100%, 150% and 200% of the CEV baseline.

III. Flight Dynamics Model

The core flight dynamics model used in the VMS, which calculates a vehicle's position and orientation for a given set of input forces and moments, was originally designed for low-speed flight applications (e.g., final approach and landing) over a flat, non-rotating Earth.[13] A more sophisticated dynamic model is necessary to capture the effects of orbital mechanics for the LEO docking task. One possible approach is to model the dynamics using Keplerian orbital elements. To maintain a basic level of commonality with the existing dynamic model, the traditional aircraft-like state variables (e.g., translational and rotational velocity components, Euler angles) were retained and the existing dynamic model was enhanced by adding the appropriate terms and new state variables for high-speed flight over a spherical rotating Earth. This approach is mathematically equivalent to using Keplerian elements to describe the orbital state. The enhanced dynamic model was developed by adapting the results of Ref. 14 and is summarized below.

A. Position Equations

The vehicle's position relative to the Earth is given in terms of latitude (λ), longitude (τ), and geometric altitude above the Earth's surface (h), as follows:

$$\dot{\lambda} = \frac{V_N}{(R_o + h)} \qquad \dot{\tau} = \frac{V_E}{(R_o + h)\cos\lambda} \qquad \dot{h} = -V_D \tag{1}$$

where V_N, V_E, V_D are North, East, and Down components (i.e., along vehicle-carrying axes) of the vehicle's Earth-relative translational velocity, and R_o = 6,371,001 m is the mean radius of the Earth (in the WGS84 coordinate system[15]). For the vehicle-carrying frame, the x and y axes lie in the local horizontal plane and point North and East respectively, while the z-axis points towards the center of the Earth. A diagram of these coordinate frames is shown in Figure 7.

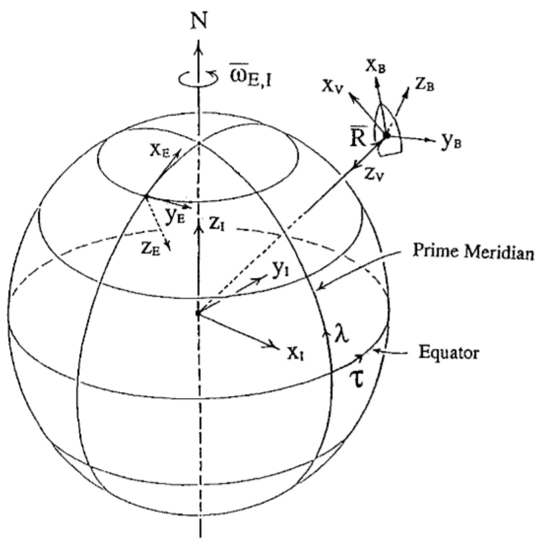

Figure 7. Coordinate frames used to describe the spacecraft state.

B. Moment Equations

The moment equations are given by:

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \dfrac{(I_y I_z - I_z^2 - I_{xz}^2)qr + I_{xz}(I_x - I_y + I_z)pq}{(I_x I_z - I_{xz}^2)} \\ \dfrac{(I_z - I_x)pr + I_{xz}(r^2 - p^2)}{I_y} \\ \dfrac{(I_x^2 - I_x I_y + I_{xz}^2)pq - I_{xz}(I_x - I_y + I_z)qr}{(I_x I_z - I_{xz}^2)} \end{bmatrix} + \begin{bmatrix} \dfrac{I_z L - I_{xz} N}{I_z I_x - I_{xz}^2} \\ \dfrac{M}{I_y} \\ \dfrac{I_x N - I_{xz} L}{I_x I_z - I_{xz}^2} \end{bmatrix} \tag{2}$$

where p, q, r are body axes components of the vehicle's rotational velocity relative to the inertial frame. The inertial frame has its origin fixed to the center of the Earth, but does not rotate with the Earth. L, M, N are body axes components of the total moment acting on the vehicle, and $I_{()}$ are moments of inertia. The above equations are for a vehicle that is symmetric in the body x-z plane, so $I_{xy} = I_{yz} = 0$.

C. Attitude Equations

The Euler angle equations have the same form as the traditional low-speed flight equations; however p, q, r are replaced by p_V, q_V, r_V, which are body axes components of the vehicle's angular velocity relative to the vehicle-carrying frame. Hence:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} p_V \\ q_V \\ r_V \end{bmatrix} \tag{3}$$

where ϕ, θ, ψ are the standard (3–2–1) Euler angles for roll, pitch, and yaw, respectively[16]; and,

$$\begin{bmatrix} p_V \\ q_V \\ r_V \end{bmatrix} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} - \begin{bmatrix} c\theta c\psi & c\theta s\psi & -s\theta \\ s\phi s\theta c\psi - c\phi s\psi & s\phi s\theta s\psi + c\phi c\psi & s\phi c\theta \\ c\phi s\theta c\psi + s\phi s\psi & c\phi s\theta s\psi - s\phi c\psi & c\phi c\theta \end{bmatrix} \begin{bmatrix} (\dot{\tau} + \omega_e)\cos\lambda \\ -\dot{\lambda} \\ -(\dot{\tau} + \omega_e)\sin\lambda \end{bmatrix} \tag{4}$$

In the above equation, $\omega_e = 7.2921159 \times 10^{-5}$ rad/sec is the angular speed of the Earth's rotation about its axis.

D. Force Equations

The accelerations of the vehicle in the North-East-Down reference frame are given by:

$$\dot{V}_N = \left(\frac{F_N}{m}\right) - \left\{\left(\frac{V_E^2 \tan\lambda - V_N V_D}{R_o + h}\right) + 2\omega_e V_E \sin\lambda + \omega_e^2 (R_o + h)\sin\lambda\cos\lambda\right\}$$

$$\dot{V}_E = \left(\frac{F_E}{m}\right) + \left\{\left(\frac{V_N V_E \tan\lambda + V_E V_D}{R_o + h}\right) + 2\omega_e (V_D \cos\lambda + V_N \sin\lambda)\right\} \tag{5}$$

$$\dot{V}_D = \left(\frac{F_D}{m}\right) + g_o\left(\frac{R_o}{R_o + h}\right)^2 - \left\{\left(\frac{V_N^2 + V_E^2}{R_o + h}\right) + 2\omega_e V_E \cos\lambda + \omega_e^2 (R_o + h)\cos^2\lambda\right\}$$

where m is the vehicle mass and $g_o = 9.8202661$ m/sec^2 is the acceleration due to gravity at the Earth's surface (i.e., at distance R_o from Earth center). F_N, F_E, F_D are vehicle-carrying axes components of the total non-gravitational force acting on the vehicle, given by:

$$\begin{bmatrix} F_N \\ F_E \\ F_D \end{bmatrix} = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \tag{6}$$

where F_x, F_y, F_z are body axes components of the total non-gravitational force acting on the vehicle.

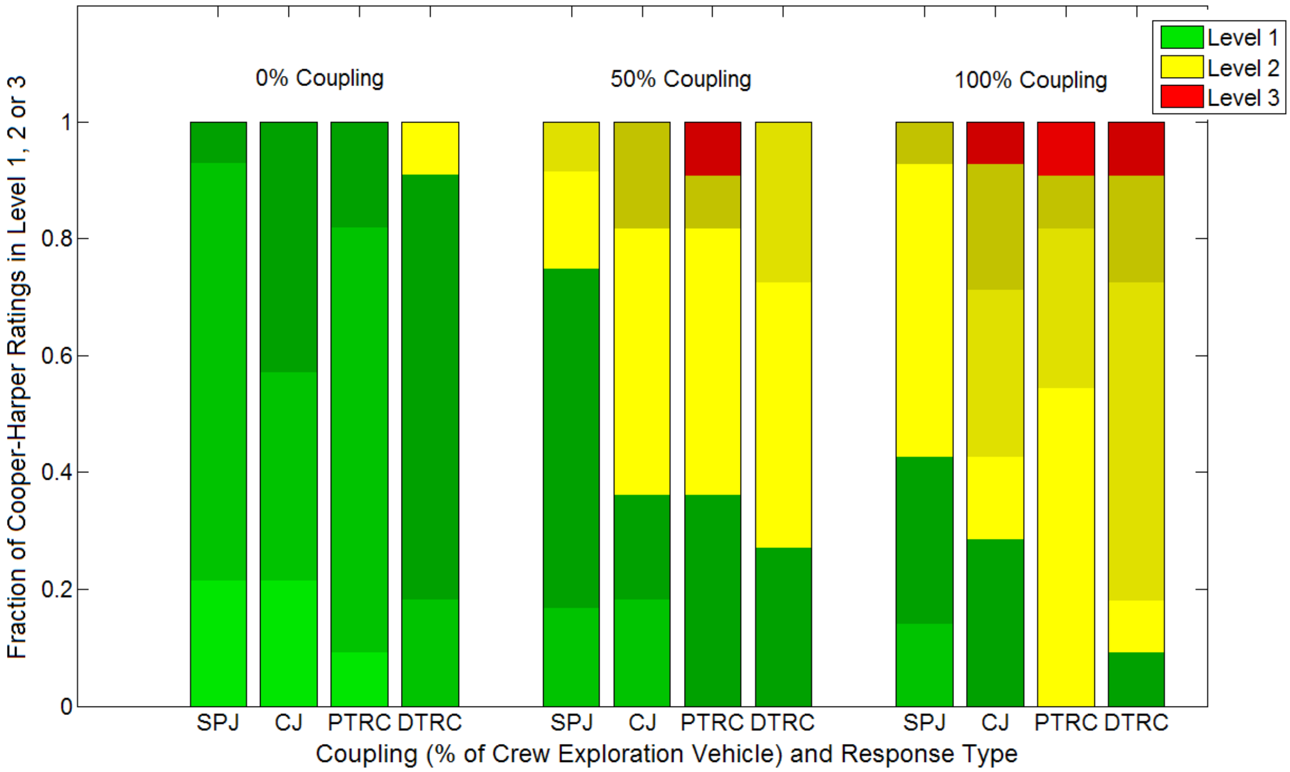

Figure 8. Cooper-Harper ratings as a function of coupling and response type. Lighter shades of a given color represent better ratings within that particular level (SPJ = Single Pulse Jets, CJ = Continuous Jets, PTRC = Proportional Translation Rate Command with position hold, DTRC = Discrete Translation Rate Command with position hold).

IV. Results

The data collection period in the VMS lasted from October 29 through November 30, 2008, with each pilot requiring approximately eight hours of total test time for initial briefing, primary and secondary data collection, debriefing and documentation. Quantitative Cooper-Harper ratings (CHR), NASA Task Load Index ratings (TLX) and the final docking performance parameters were recorded during the simulation. Each pilot provided substantial subjective feedback on the performance of, and their preferences for, each control system, the complicating effects of the translation-into-rotation coupling and their overall impressions of the docking task. This section will discuss the qualitative and quantitative results of each of the sets of test conditions.

A. Handling Qualities by Response Type and Degree of Coupling

The major result of this experiment was the variation in handling qualities as a function of translational response type and the degree to which translation inputs coupled into rotational motion. Those results are summarized in Figure 8 as a stacked bar chart with the different response types grouped according to the level of coupling and each color representing a different handling qualities level. The ratings within levels are represented by different shades of that color, with lighter shades indicating better ratings.

The clearest trend in Figure 8 is the degradation in handling qualities as coupling increases, regardless of response type. The four bars on the left of the figure, representing 0% coupling, indicate that pilots overwhelmingly rated that configuration Level 1 regardless of the response type. The different shades of green within Level 1 for the different response types shows that some differences exist across those configurations for 0% coupling, and in particular the discrete TRC/PH response type was rated somewhat worse than the others, but clearly 0% coupling is the best condition tested. When the coupling is increased to 50% the proportion of Level 2 ratings increases for every response type. The SPJ response type is comparatively better than the other three for this level of coupling, with only about 25% of pilots giving a Level 2 rating for SPJ compared with 70% for the others. When the coupling is further increased to 100% all four response types are unequivocally Level 2. The trend of worsening handling qualities as coupling increases regardless of response type indicates that the degree of coupling is the dominant

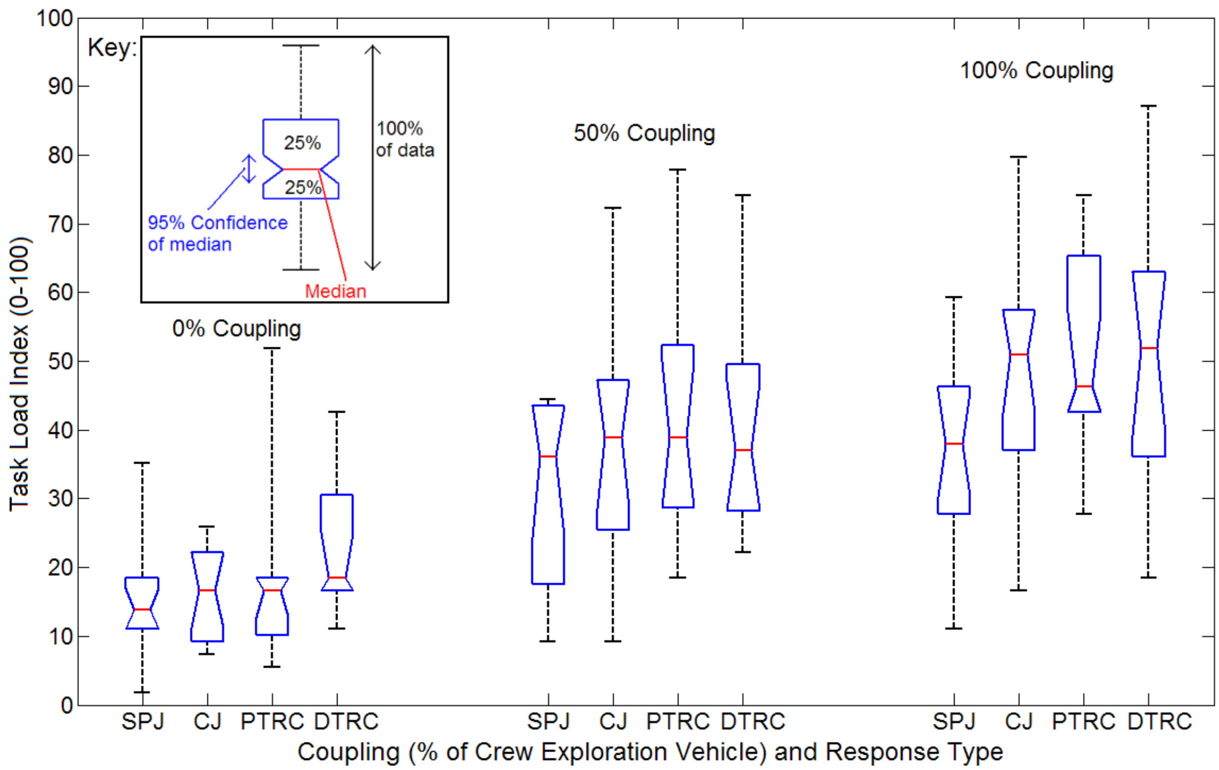

Figure 9. Box and whisker plot of Task Load Index data.

factor in this handling qualities evaluation. The effect of the response type is a secondary factor in determining handling qualities.

The Task Load Index (TLX) consists of six variables that are each rated by pilots to indicate the specific sources of workload (e.g. mental, physical or temporal). The six elements of the TLX were averaged to get an overall measure of workload for each test condition for each pilot, and the ratings of all pilots for a given test condition then aggregated into a box-and-whisker plot. The result is shown in Figure 9. The workload ratings results parallel those of the handling qualities ratings (shown in Figure 8), showing that workload increases significantly when the coupling increases from 0%, and do not differ significantly with response type for a given coupling condition. It is interesting to note the large range in TLX values assigned by the different pilots; this fact is at least partially due to the lack of an objective definition of a given numerical TLX value. That lack of an anchor for a particular TLX rating means comparisons are better done across configurations than interpreted for a single configuration.

The notches in the boxes of Figure 9 indicate a confidence level of the range of values the median may take using standard variance analysis. If two data sets do not have overlapping notches then one may be 95% confident that the medians of the two sets are in fact different; if two notches overlap then there is no statistically significant difference between the medians at the 95% confidence level. At that confidence level, all response types in the 0% coupling condition were assigned a lower workload rating than any response type in the 50% or 100% coupling cases. None of the response types in either 50% or 100% coupling conditions were statistically different from each

Table 1. Desired and Adequate docking performance bounds.

Docking Parameter:	**Desired**	**Adequate**
Radial Offset	**±0.125 ft**	**±0.125 to ± 0.267 ft**
Roll/Pitch/Yaw Angle	**±2.0 deg**	**±2.0 to ±3.0 deg**
Axial Closure Rate	**0.075 to 0.125 fps**	**0 to 0.075 fps or 0.125 to 0.15 fps**
Radial Closure Rate	**±0.0325 fps**	**±0.0325 to ±0.1125 fps**
Roll/Pitch/Yaw Rate	**±0.05 deg/sec**	**±0.05 to ±0.15 deg/sec**

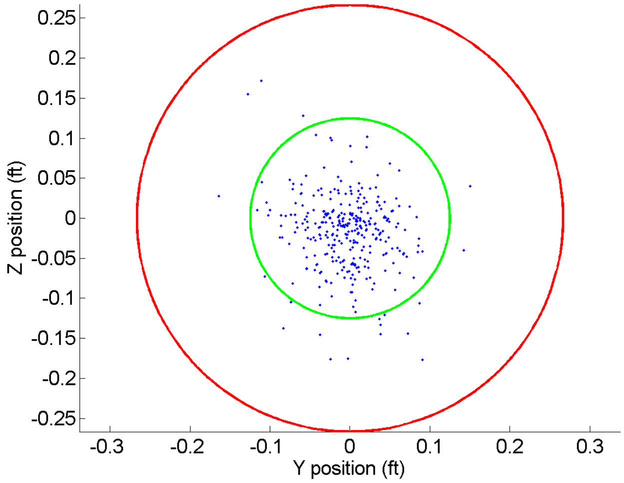

Figure 10. Radial offset dispersion data at contact (N = 439).

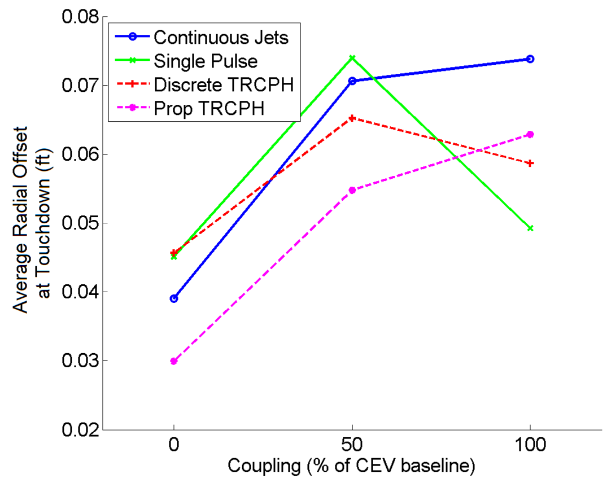

Figure 11. Average radial offset from docking ring centerline at contact.

other at the 95% confidence level. The clear implication from these plots, as from the CHR plots above, is that workload and handling qualities are strong functions of the degree of coupling between attitude and translation inputs, and are only weaker functions of the response type. Put another way, the effect of translation-into-attitude coupling is so strong that it overwhelms almost any distinction between these very different response types.

During the debriefings every astronaut trained in the docking task expressed a preference for the single pulse response type, a fact most likely due to its similarity to the Space Shuttle's response type and the large number of hours spent training on that system. Pilots without prior experience docking the Space Shuttle generally preferred the single pulse or proportional TRC/PH systems. The pilots were quickly able to discern the level of coupling present in the vehicle even though they were not told what that level would be. Pilots often referred to the response with 0% coupling as "predictable," and commented that they did not have to guess where the nose of the vehicle would trend. The higher coupling levels appeared to increase workload and worsen handling qualities because pilots were unable to confidently make inputs and estimate what the resultant motion would be.

B. Docking Performance by Response Type and Degree of Coupling

The Cooper-Harper rating scale requires an explicit definition of "desired" and "adequate" performance for the given task; such requirements, shown in Table 1, drive the pilot to work harder to achieve those performance metrics and so may be important drivers of overall workload even if the actual performance was always within the desired range. The dispersion in the radial offset of all dockings performed during data collection is shown in Figure 10, along with range rings that define desired (green) and adequate (red) performance. Pilots were able to dock within the desired range in 94% of runs, and no run had a radial offset outside the adequate range; however this does not imply that the task was straightforward with low workload or that the vehicle handling qualities were satisfactory. In many cases pilots achieved that final docking performance only with significant workload, a fact reflected in TLX ratings near 90 and CHRs of up to eight.

The average radial offsets achieved as a function of response type and coupling conditions are shown in Figure 11. That plot shows that under any coupling condition and with every response type the average performance was well within the desired range, and there is an improvement in performance between the 0% coupling case and either the 50% or 100% coupling cases. In general, there is not an appreciable improvement in performance between the 50% and 100% coupling cases. These results must be qualified by the fact that any radial offset under 0.125 ft is equivalently "desirable," so there was no incentive to drive that offset to zero, and by the apparently large improvement in performance for the single pulse response type between 50% and 100%, which is currently unexplained but probably due to chance. These results confirm the CHR and TLX results from the previous section suggesting that benefits are seen for 0% coupling cases, but that at any coupling value greater than 50% performance and handling qualities are degraded.

The performance parameter that pilots had the most difficulty controlling was the angular velocity; in 85% of runs their performance was in the desired range, and in 2% of cases it was outside adequate. The dispersions in yaw and pitch rate are displayed in Figure 12. Because the docking task in the last ten feet consists only of translation the pilots were not able to directly control the attitude rates at dock; however, they were able to limit the errors by adjusting their piloting technique to avoid making any inputs in the last five seconds (roughly 0.5 ft) before docking

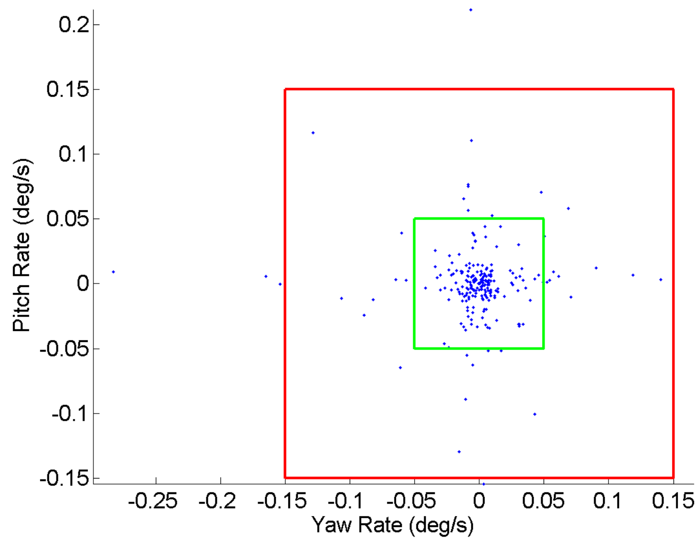

Figure 12. Angular velocity dispersion data at contact (N = 439).

occurred. While this rate requirement could be met by adjusting control system parameters the technique that avoids such errors is consistent with the way pilots are trained to dock: make few translation inputs and, when in doubt, just fold your hands and watch the situation evolve.

Another performance measure, albeit one that was explicitly communicated to the pilots as not being part of the evaluation, was the total propellant used in each docking run. This variable was measured because minimizing RCS propellant use is traditionally an important requirement for pilots and therefore one that is incorporated into any space maneuvering task. The average propellant consumed as a function of response type and coupling condition is shown in Figure 13, and the results are again consistent with CHR and TLX ratings. Each response type shows monotonically increasing propellant use with increasing coupling, and the open loop response types (single pulse jets and continuous jets) consume far less propellant than the closed loop types (proportional and discrete TRC/PH). This result is important as many of the pilots indicated that they gave the TRC/PH response types poorer ratings because of the additional propellant usage those entailed.

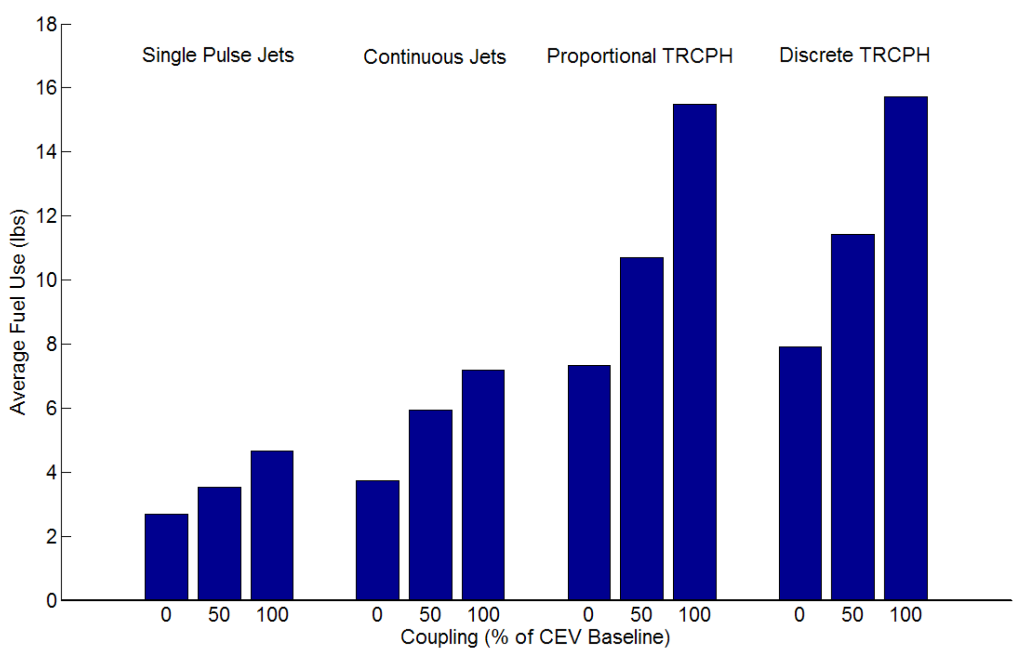

Figure 13. Average propellant use as a function of response type and coupling level.

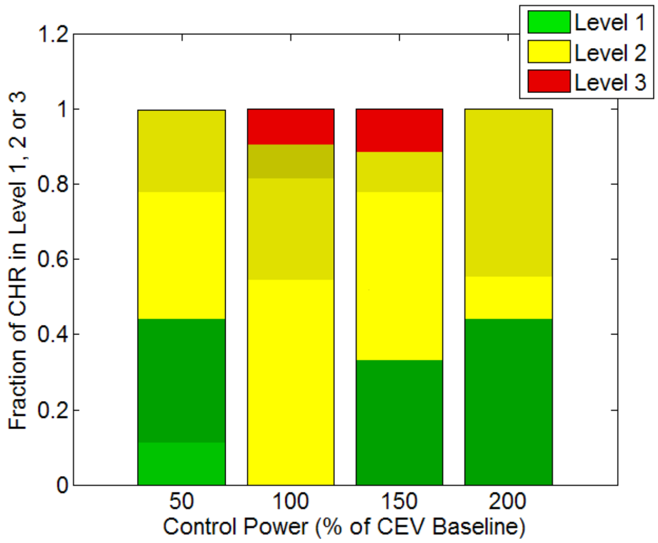

Figure 14. All Cooper-Harper ratings assigned to the proportional TRC/PH control system as a function of control power.

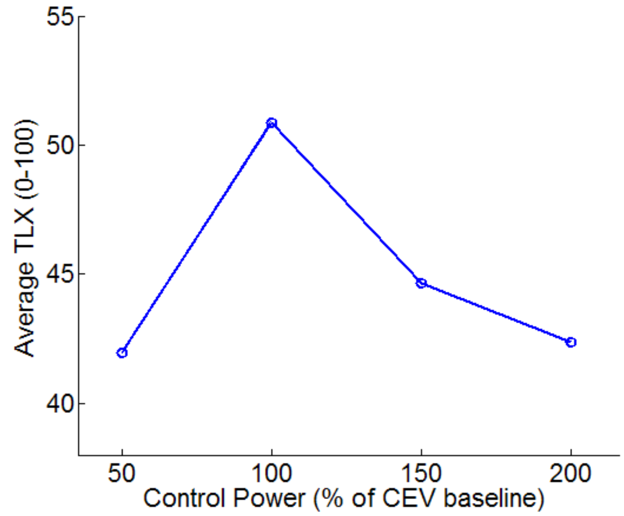

Figure 15. Task Load Index ratings assigned the proportional TRC/PH response type as a function of RCS jet thrust level.

C. Variation in Control Power Results

A secondary test matrix was designed to determine the effect on handling qualities of variations in thrust level of the RCS jets. This test was conducted using the proportional TRC/PH response type because it was anticipated that that control system would be most sensitive to jet thrust changes. Thrust changes with the single pulse jet response type, for example, would be barely noticeable to the pilot because the control system would simply adapt the duration of the jet pulses to get the predetermined velocity change. Greater control powers with the TRC/PH response type would allow the vehicle to respond more quickly to pilot inputs, but they would also make the system feel more sensitive and perhaps prone to over-corrections. Less control power could provide finer control over the vehicle, but it would require more pilot compensation to make up for lags in the vehicle's response. The CHRs assigned to the vehicle with control powers ranging between 50% and 200% of the CEV baseline configuration are shown in Figure 14. There is no clear trend in those data except the lack of even a single Level 1 rating in the 100% control power case and roughly equal distributions of ratings among the levels in the other three cases. Despite these inconclusive results, it is clear that most pilots feel the proportional TRC/PH response type is close to the Level 1/2 boundary but on the Level 2 side, and that the handling qualities are not strong functions of RCS jet size.

The workload ratings as measured by TLX also show some variability as a function of RCS jet thrust level, but the changes are relatively small. TLX ratings, averaged across pilots, are shown in Figure 15. While it may appear that the nominal 100% thrust level is actually the worst level among those tested, the peak at 100% is more likely due to learning curve effects. The four levels of thrust were not all tested consecutively, instead the 50%, 150% and 200% configurations were run in secondary tests after the primary test matrix had been filled out – the primary test matrix being the source of the 100% control power evaluation. Because 100% thrust was always run before the other three configurations, and consequently pilots had the least amount of experience on the task when flying the 100% case, it is not surprising that pilots would improve their understanding of and performance in the task by the time they evaluated the secondary test conditions. An analysis of variance shows that the workload differences between the different thrust rating conditions are not significant at the 95% level.

The pilot performance in terms of propellant usage and radial offset are shown in Figure 16 and Figure 17, respectively. The propellant used closely parallels the assigned workload ratings, and piloting technique is probably responsible for the peak propellant use at 100% control power. As the pilots gain experience with the task they adapt their technique to minimize propellant use, and because pilots had more experience in the task by the time the secondary control power test matrix was run the best configurations appear to be the 50%, 150% and 200% thrust levels. These results are not statistically significant at a 95% confidence level. A clearer trend is evident in the average radial offset achieved by the pilots in Figure 17. As the control power increases the average radial offset decreases slightly, although the usual caveats must be made because that parameter is judged desirable whenever it

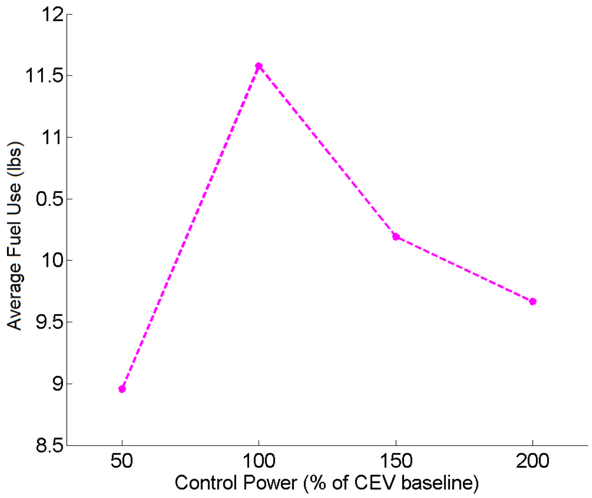

Figure 16. Average propellant use (in pounds) among all pilots and test runs as a function of control power for the proportional TRC/PH response type.

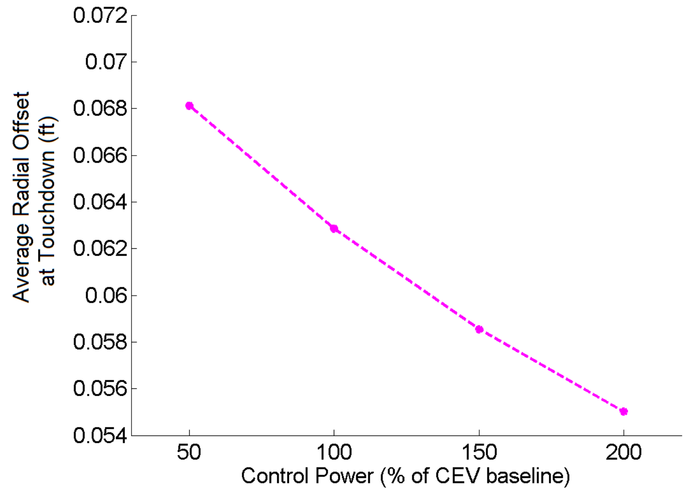

Figure 17. Average radial offset at docking contact among all pilots and test runs as a function of control power for the proportional TRC/PH response type.

is below the 0.125 ft threshold, as all the average data points were. However, because the pilots do attempt to minimize the dispersions from a perfect docking it is apparent that with increasing control power slightly better docking performance seems to be achievable. The differences between those data points are not significant at a 95% confidence level, and the overall difference in average radial offset at the maximum and minimum powers was only 0.16 in.

V. Conclusions

This paper presented the results of a piloted evaluation of handling qualities for the docking of a Crew Exploration Vehicle-like spacecraft with the International Space Station. The parameters studied were translation control response type, degree of translation-into-rotation coupling, and the control power (thrust level) of the Reaction Control System jets. The four response types determine how a pilot input to the hand controller is converted into a position, velocity or acceleration command to the vehicle; the degree of coupling is the relative size of the disturbance moment that is created when thrusters fire to create forces for translation.

A strong relationship exists between increasing levels of translation-into-rotation coupling and degraded handling qualities. This relationship is so strong that it holds for all response types, and, with few exceptions, any response type with less coupling is rated better than any response type with more coupling. For all response types the 0% coupling condition received solidly Level 1 ratings; the 50% configuration straddled Levels 1 and 2; and the 100% coupling condition was primarily Level 2. The single pulse jet response type received the best handling qualities ratings in the strong coupling cases and the most positive comments during pilot debriefings. All four response types allowed pilots to achieve desired performance in nearly every run so poor end conditions were not responsible for the degraded handling qualities. Rather, the pilot compensation required to overcome coupling to achieve that desired performance is the cause of the result; most of the cognitive workload arose from difficulty separating the translational and rotational components of the relative position error as seen through the centerline camera.

The results of the thrust level variation experiment were inconclusive. The handling qualities, TLX workload and propellant use parameter were better at the 50%, 150% and 200% control power levels rather than 100% control power, but this is likely due to the fact that the pilots had more experience and training in the task by the time they reached the secondary experiment matrix. It was in this secondary matrix that pilots had a chance to fly control powers other than 100%. The radial offset at docking improved with control power, but the results were not statistically significant and the total variation in the average docking offset was less than 10% of the allowable offset.

Further research will be required to determine the maximum amount of coupling a vehicle may possess and still be rated Level 1, an amount that is estimated to be between the zero and 50% cases evaluated in this simulation. Other response types should be designed and tested to see if they can mitigate the effects of coupling, whether by automatically removing the disturbance moments as soon as they occur or reducing the size of the attitude hold deadband until the unwanted motion is no longer objectionable. A different approach may be to design flying aids that assist the pilot in visualizing the deadband limits or separate the apparent motion in the centerline camera into its translational and rotational components. These techniques may be more operationally feasible for achieving Level 1 handling qualities than moving the ring of thrusters to be coincident with the vehicle center of mass.

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