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# Dynamic Coupling and Control Response Effects on Spacecraft Handling Qualities During Docking

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**NASA is developing a new generation of spacecraft 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, called response types, that map pilot inputs to thruster firings in a way that gives predictable and useful vehicle responses. 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 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 handling qualities.**

## Nomenclature

| | | |
|---|---|---|
| $F_N, F_E, F_D$ | = | vehicle-carrying frame components of nongravitational force acting in the north direction, in the east direction, and along the local gravity vector, respectively, lbf |
| $F_x, F_y, F_z$ | = | body axis components of nongravitational force acting along the vehicle $x$, $y$, and $z$ axes |
| $g_0$ | = | acceleration due to gravity at distance $R_o$ from Earth's center, $\mathrm{ft/s^2}$ |
| $I_{()}$ | = | vehicle moments of inertia, slug-ft$^2$ |
| $L, M, N$ | = | body axis component of total roll, pitch, and yaw moments acting on vehicle, ft-lbf |
| $m$ | = | mass of the docking vehicle |
| $p, q, r$ | = | body axis component of vehicle roll, pitch, and yaw rates with respect to inertial frame, rad/s |
| $p_v, q_v, r_v$ | = | body axis component of vehicle roll, pitch, and yaw rates with respect to vehicle-carrying frame, rad/s |
| $R_0$ | = | mean radius of Earth, ft |
| $V_N, V_E, V_D$ | = | vehicle-carrying frame velocity in the north and east directions with respect to Earth's surface, and in the direction of the local gravity vector, respectively, ft/s |
| $\lambda, \tau, h$ | = | latitude and longitude, rad, and geometric altitude above a spherical Earth, ft |
| $\varphi, \theta, \psi$ | = | Euler roll, pitch, and yaw angles, rad |
| $\omega_e$ | = | angular velocity of Earth's rotation with respect to sun–Earth vector, rad/s |

## 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 these factors on handling qualities have been studied in atmospheric flight vehicles for over 70 years [1–4], and have led to the development of reference standards for the handling qualities of both fixed-wing aircraft [5] and rotary-wing aircraft [6]. Broadly speaking, these standards define a subset of the dynamics and 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.

NASA and private commercial interests are designing a new generation of piloted spacecraft [7]. These vehicles include the Crew Exploration Vehicle (CEV, also known as Orion) to replace the Space Shuttle and ferry astronauts to Earth and lunar orbits, and the Altair spacecraft to provide transportation to the lunar surface from lunar orbit. The ability of pilots 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 subcomponent of the spacecraft fails [8]. 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.

Although there are no standards for spacecraft handling qualities, a large body of knowledge was accumulated during NASA's Gemini and Apollo programs on ways to ensure that the handling qualities of

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particular spacecraft designs would allow safe and routine rendezvous and docking [9–13]. In large part, those studies attempted to determine the preferred mode for manual control of attitude [14–19], the utility of television cameras to conduct remote and obstructed-view dockings [19,20], the optimum combination of out-the-window visual aids to allow instrument-free dockings [14,16–18,20], ideal inceptor characteristics [21], limits on target oscillatory motion [15], the effect of docking during orbital night versus day [16,18], the consequences of failed thrusters [14], and the handling qualities ratings of the specific Gemini and Apollo vehicles as a function of these parameters [14,17,19]. Those tests showed that the rate command with attitude hold (RCAH) manual control mode, also known as a response type, was favored over a simple rate command or direct acceleration command mode [19], and all vehicles starting with Gemini have used or are currently able to use that mode of controlling attitude. Television cameras were shown to be viable sensors for conducting dockings once the pilot learned to compensate for the degraded visual scene and difficulty in estimating range and range rate; [20] remote cameras are being used on the Space Shuttle and are part of the baseline design of the Orion vehicle. The standoff cross and collimated reticle that are Shuttle astronauts' primary means for determining relative state errors during the final phase of docking were identified during and used in the Apollo program for crew and service module docking with the lunar module (LM) [18]. Several fixed-base [17,19] and 6-degree-of-freedom (DOF) [14,17] simulators were used to evaluate these combinations, and results indicated that with the RCAH mode and a good set of visual cues the handling qualities of the vehicles were approximately 2.0 on the Cooper scale, and that they degraded to about 4.5 when direct acceleration command for attitude control was used [19]. These results were repeatedly confirmed during follow-up simulations and confidence in the design solutions was so high that subsequent vehicles adopted them almost without modification. This work forms an excellent baseline from which to start designing docking systems that provide desired handling qualities, but improvements in navigation state accuracy, control mode sophistication, and instrumentation since Apollo offer the possibility of making the task of docking spacecraft even easier for the astronaut.

An effort to build on previous handling qualities research and to develop design guidelines in this area 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 on an experiment investigating the docking of two spacecraft in low Earth orbit (LEO); specifically, the effect of translation-into-rotation coupling and translational response-type design on handling qualities is evaluated. Companion papers report on experiments investigating the final approach and touchdown phase of lunar landing [22], a 6 DOF piloting task for docking with a space station [23], and a study of pilot aids for docking with a space station [24]. Although early research programs established RCAH as the preferred response type for attitude control, no study was done of similar control modes that command a translational velocity and allow position hold. Such response types are desirable in rotorcraft [6] and feature in the design standards as a way to compensate for poor visual cue environments or unaugmented vehicle dynamics, so it is natural to evaluate this type of control mode for the docking task. The problem of translation-into-rotation coupling was present in other spacecraft designs but was never experimentally varied to determine its contribution to degraded handling qualities; the coupling level was always fixed at the value of the particular vehicle. In addition to handling qualities effects that have not been investigated, the results of the Gemini and Apollo programs are incomplete from a modern perspective because the docking terminal conditions for those probe-and-drogue systems are much looser than they are for modern petal-type systems like the androgynous peripheral attachment system (APAS) used on the Shuttle and the International Space Station (ISS). In addition, instrumentation has improved significantly beyond the primarily visual cueing environment used in the past, the Cooper scale that was used for all early evaluations has been superseded by the Cooper–Harper Handling Qualities Rating scale that is in wide use today, and today's ubiquitous digital flight control systems have fundamentally different characteristics than the analog systems used in the past. The changes that have occurred since the foundational work of the 1960s on spacecraft handling qualities during docking warrant further investigation into this contemporary problem.

The approach taken in this paper is to examine several design choices in the neighborhood of NASA's Orion vehicle without purporting to evaluate the handling qualities of that vehicle specifically. What will be termed the active docking vehicle (ADV) for the rest of this paper used only the mass properties, reaction control system (RCS) thruster locations and thrust vectors, and terminal docking conditions from an early design of Orion. The pilot displays, control system specifications, and inceptor characteristics were not available for this experiment, and so generic systems adapted from legacy vehicles were used instead. The next section describes the specific piloting task required to dock two spacecraft in LEO, including initial conditions and cockpit displays, the vehicle model and control system design, and the experiment matrix. A second section describes the flight dynamics model that was employed in the simulator, and the final sections discuss results and conclusions.

## II. Experiment Design

The principal objective of the experiment was to map out variations in handling qualities for combinations of translational control response types and RCS thruster ring locations relative to the ADV's center of mass (c.m.) corresponding to various levels of translation-into-rotation coupling. The piloting task was the final stage of docking operations during which the ADV approaches a target docking vehicle (TDV), in this case represented by a visual model of the ISS, along the station's orbital velocity vector, generically known as the $V$-bar approach. Where appropriate for these generic vehicles, the operational characteristics of the approach and docking, like closure rate and contact accuracy requirements, were based on the Space Shuttle docking with the ISS. This docking approach is done 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 flying task assigned to the pilot was to control those 2 DOF in translation. The absolute motion of both vehicles was modeled, including primary orbital mechanics effects, using the flight dynamics model described in Sec. III. In this simulation, the TDV was in a circular orbit 189 n miles 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, and no pilot had flown the simulation before data collection. Pilots provided Cooper–Harper ratings [1], NASA task load index (TLX) ratings [25], and qualitative comments. The 14 pilots have an average of 7500 h 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 ADV and TDV docking ports was 10 ft and the relative axial closing speed was 0.1 ft/s, resulting in a nominal run time of 100 s. There was no error in ADV attitude or angular rates relative to the TDV. To provide sufficient piloting challenge and expose potential handling qualities issues, a 4.2 ft radial offset, defined as the perpendicular distance between the axis of the TDV dock and the center of the docking ring of the ADV, was applied to all initial conditions. This resulted in four initial positions of the ADV dock center relative to the TDV docking axis: each point is displaced plus or minus three feet laterally and three feet vertically from the dock centerline. One of these initial positions, always below and left of the docking port, was used for training and familiarization runs, and 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 TDV approximately as it would appear from the left (commander's) seat of the ADV. A three-axis rotational hand controller was installed on the right side of the pilot seat, and a three-axis translational hand controller 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 Fig. 1; note that this distance is farther than the pilots would ever be from docking during data collection runs.

The panel in front of the pilot seat had three 6.5 in. color flat panel displays, the contents of which may be seen in Fig. 2. The right panel (Fig. 2c) displayed an Attitude Director Indicator (ADI) and also included tapes showing range and range-rate of the ADV docking port relative to the center of the TDV docking port. The center panel (Fig. 2b) displayed a simulated view from a camera mounted on the centerline of the ADV dock, overlaid with a green reticle (crosshairs). The TDV dock is the large ring with three petal-like objects in the center of this display. The left panel (Fig. 2a) displayed streaming data of key docking parameters, such as radial offset error and relative angular rates.

### C. Visiting Vehicle and Control System Models

Generic ADV dynamic models, control systems for translation and attitude maneuvers, and pilot displays were each developed for this experiment. Described in detail later in this section, the control system designs were representative of a range of possible implementations, from those used since Gemini to several adapted from advanced rotorcraft systems. A side view of the ADV showing the body axis coordinate system and important subsystems is provided in Fig. 3.

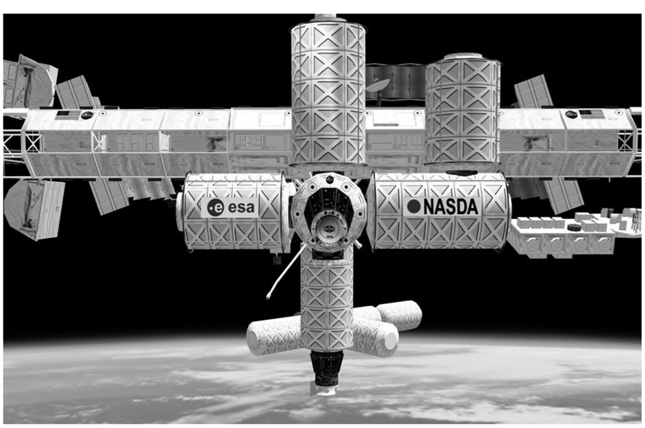



**Fig. 1 Out-the-window-view of TDV at 100 ft from docking.**

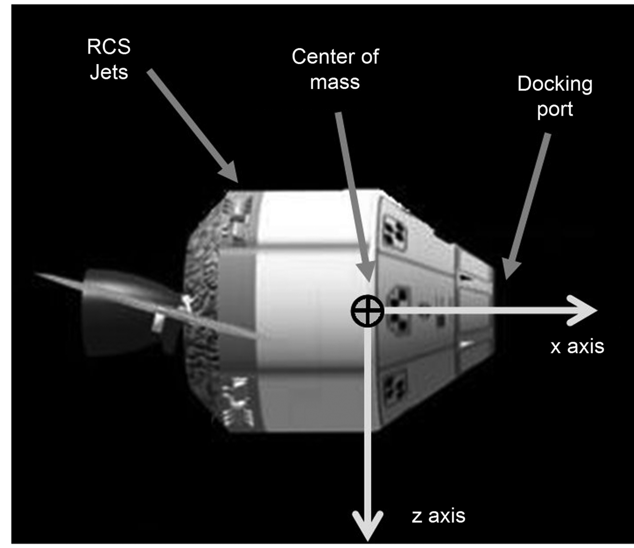
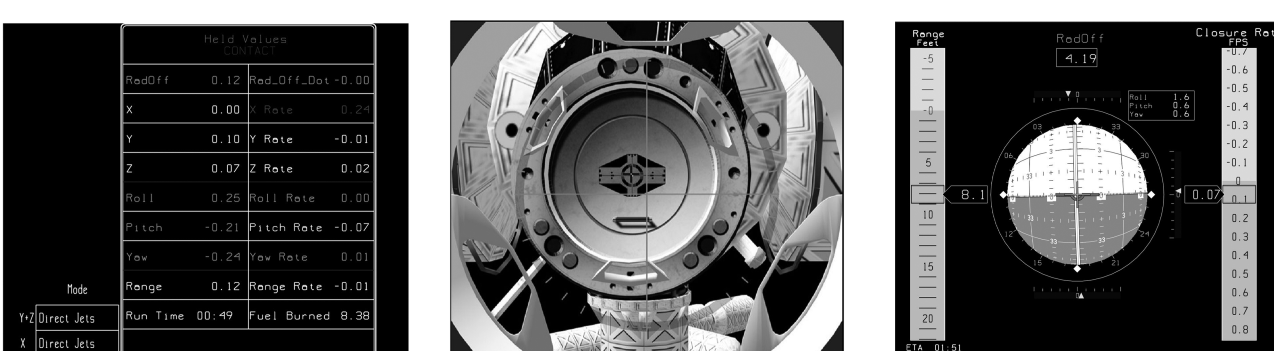



**Fig. 3 ADV side view.**

Four response types were provided in the translation axes: single pulse jets (SPJ), continuous jets (CJ), proportional translation rate command with position hold (proportional TRC/PH) and discrete TRC/PH. In the SPJ response type, displacement of the inceptor out of the neutral position commands a fixed velocity increment of $0.01\ \mathrm{ft/s}$ in the appropriate axis; subsequent velocity increments can only be commanded by returning the inceptor to the neutral position and then displacing it again. This response type allows the pilot to command a particular translation rate by making several discrete inputs, and to remove the rate with the same number of inputs in the opposite direction. The control system achieves each incremental velocity change by commanding several RCS thrusters to fire for a precalculated duration based on the jet thrust and vehicle mass, and the resultant force is directed through the ring of RCS thrusters, not the vehicle c.m. This response type is similar to that used by the Space Shuttle today and is the baseline response type planned for NASA's Orion and Altair spacecraft. The CJ response is basically a discrete acceleration command control system: when the inceptor is outside the neutral position the RCS thrusters fire continuously, providing a constant value of acceleration. When the inceptor returns to neutral the thrusters turn off and the vehicle drifts freely. This response type was often referred to as direct mode in earlier vehicles. The two closed-loop translational velocity control systems adapted from advanced rotorcraft systems are proportional TRC/PH and discrete TRC/PH, and they differ only in the velocity that may be commanded, not in the implementation of position hold. Proportional TRC/PH commands a translational velocity proportional to the inceptor displacement, up to a maximum of $0.2\ \mathrm{ft/s}$ at full inceptor throw; returning the inceptor to neutral captures the spacecraft c.m.




a) b) c)

**Fig. 2 Cockpit displays showing a) real-time digital readouts of relevant vehicle states, b) centerline camera display with superimposed reticle, and c) ADI display with range and range-rate tapes.**

position relative to the docking target and the control system fires thrusters as required to hold that TDV-relative position within a 0.06 ft deadband. The velocity deadband when in translation rate command mode is 0.01 ft/s. The discrete TRC/PH response type is identical to the proportional type except that the velocity command is always fixed at 0.1 ft/s when the inceptor is out of the neutral position. The generic switching curve logic used to hold the position for the latter two response types is described at the end of this section; the velocity command for these systems is accomplished with a simple deadband that uses translational velocity only.

Only a single response type, proportional RCAH, was used for attitude control in this experiment. This response type commands the RCS thrusters to fire to achieve an angular rate proportional to the inceptor displacement; returning the inceptor to neutral captures the spacecraft attitude and fires thrusters as required to maintain that attitude within a deadband of 0.25 deg. Because the vehicle attitude was initially aligned with the docking axis and the pilots were instructed not to use the rotational controller the system was always in attitude hold mode.

The closed-loop control laws, both translational (proportional and discrete TRC/PH) and rotational (RCAH), used phase-plane logic based on time-optimal [26] (parabolic) switching curves to hold position and attitude (see Fig. 4 for the attitude hold switching curves; curves for translation are identical except for the units). The deadband area within the switching curves represents the combination of states and their derivatives for which the RCS thrusters do not fire; above and to the right of the deadband the thrusters fire to provide a negative force or moment, and below and to the left of it they provide a positive force or moment. The outer, solid lines have the parabolic shape of the time-optimal curve, but the inner, dotted lines bend steeply toward the horizontal axis to limit the rate at which the vehicle traverses the deadband. In essence, the degree of bending of the inner lines represents a trade-off between propellant use and the time required to remove state 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 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 move the vehicle c.m. to the left, but will also induce an unwanted yawing moment that moves the vehicle's nose to the right. Because the centerline camera is mounted on the nose of the ADV 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 degree of coupling is dependent not only on the location of the RCS thrusters relative to the c.m. but also to the control scheme by which forces and moments are generated in response to pilot inputs. Coupling is measured in this paper as the ratio between the disturbance angular acceleration $\mathrm{deg}/\mathrm{s}^2$ and the applied translational acceleration $\mathrm{ft}/\mathrm{s}^2$ that gives rise to the disturbance. Coupling is measured in units of deg/ft.

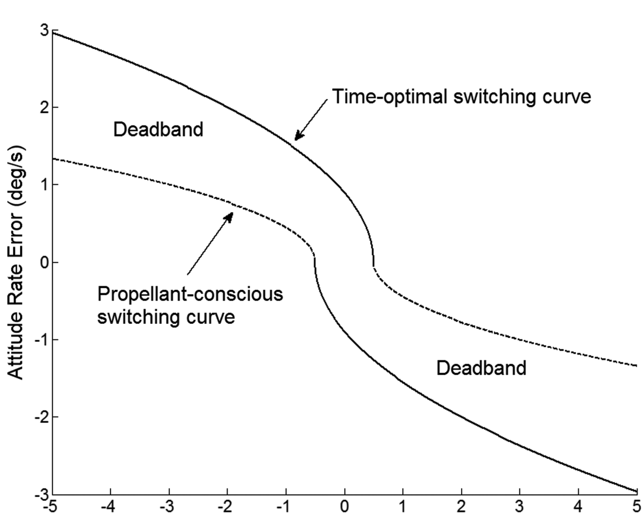



**Fig. 4 Switching curves for attitude.**

The thrust model of the vehicle was obtained by calculating the resultant forces and moments arising from a pure translation 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 for the translation-into-attitude coupling, a pure force command applied through the RCS thruster ring 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, which did not account for prioritization of commands or RCS thrusters, allowed forces and moments to be generated in any and all axes at once. However, in practice such an unlikely confluence of commands was not observed.

### D. Experiment Matrix

A schematic of the primary experiment matrix is shown in Fig. 5. Pilots were presented three different values of coupling, ranging from 0 to 5 deg/ft for a particular 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, that is, the thrust produced by each RCS jet. This was done for the configuration of proportional TRC/PH response type with baseline thrust coupling, and the control power ranged from 50 to 200% of the baseline. Because those results did not show a clear trend in terms of handling qualities, they are not presented here. However, they are available in an earlier paper [27].

## 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, nonrotating Earth [28]. 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. However, to maintain compatibility with the existing dynamic model that has been validated over decades in the VMS, the traditional aircraftlike 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 only approximations in this model are the absence of third-body gravitational effects and the treatment of Earth as a spherically symmetric body, neither of which contributes significantly to docking dynamics. The enhanced dynamic model was developed by adapting the results of [29] and is summarized in the following section.

| **Response Type** → / **Thrust Coupling** ↓ | Continuous Jets | Single Pulse Jets | Proportional TRC/PH | Discrete TRC/PH |
|---|---|---|---|---|
| 0 deg/ft | | | | |
| 2.5 deg/ft | | | | |
| 5 deg/ft | | | | |

**Fig. 5 Experiment matrix.**

### A. Position Equations

The vehicle's position relative to the Earth is given in terms of latitude, longitude, and geometric altitude above the Earth's surface, 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 $R_o$ is constant at 20,896,880 ft (defined by the WGS84 coordinate system [30]). For the vehicle-carrying frame, which is centered on the vehicle's c.m., the $x$ and $y$ axes lie in the local horizontal plane and point north and east, respectively, and the $z$ axis points toward the center of the Earth. A diagram of these coordinate frames is shown in Fig. 6, where the vehicle-carrying frame is denoted by a subscript $v$, the body frame by subscript $b$, and the Earth-Centered Inertial frame by subscript $I$. These frames are defined in the conventional way [29,30].

### B. Moment Equations

The moment equations are given by

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

The inertial frame has its origin fixed to the center of the Earth, but does not rotate with the Earth. Equation (2) is valid for a vehicle that is symmetric in the body $x$-$z$ plane, so that $I_{xy} = I_{yz} = 0$.

### C. Attitude Equations

The Euler angle equations have the same form as the traditional low-speed flight equations; however $p$, $q$, and $r$ are replaced by $p_V$, $q_V$, and $r_V$. Hence

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

and

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

In Eq. (4), $\omega_e = 7.2921159 \times 10^{-5}$ rad/s.

### D. Force Equations

The accelerations of the vehicle in the north-east-down reference frame, which corresponds to the vehicle-carrying frame in Fig. 6, are given by

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

where $g_o = 9.8202661\ \mathrm{m/s^2}$. $F_N$, $F_E$, and $F_D$ are given by the standard Euler angle sequence (3-2-1) for rotation matrices

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

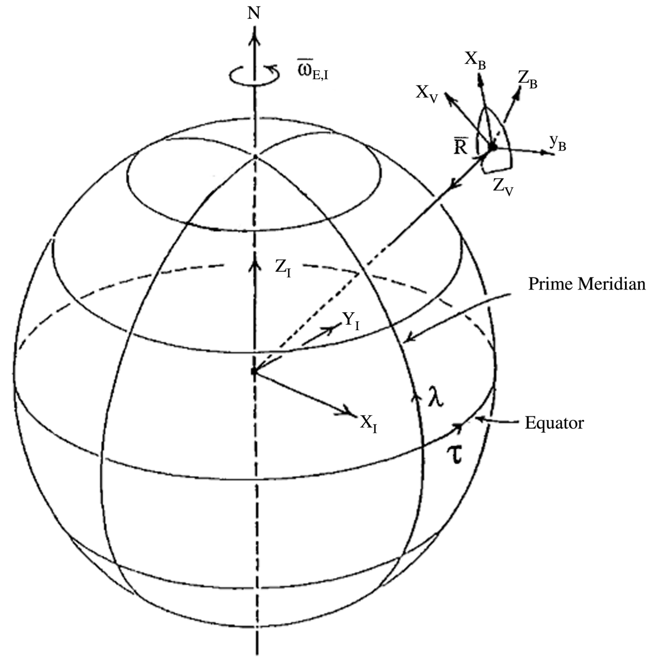



**Fig. 6 Spacecraft state coordinate frames.**

## IV. Results

The data collection period in the VMS lasted from 29 October through 30 November, 2007, 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) [1,4], NASA TLX ratings [25], and the final docking performance parameters were recorded during the simulation. The CHR scale asks the pilot to answer a series of questions regarding the controllability, performance, and workload of a task for a given vehicle, and to select a rating based on descriptors of the amount of pilot compensation required to achieve a particular performance target. A CHR of 1 represents the best possible rating with pilot compensation not being a factor for achieving desired performance, whereas a rating of 10 indicates control of the vehicle will be lost while executing the task. The TLX scale breaks workload into six different factors that the pilot rates individually between 0 (low) and 100 (high), and a composite rating is formed from the average of these factors. Each pilot also 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 goal of this experiment was to measure variations in handling qualities as a function of translational response type and the degree to which translation inputs coupled into rotational motion. The results are summarized in Fig. 7 as a stacked bar chart with the different response types grouped according to the level of coupling and each shade of gray representing a different handling qualities level, where a CHR of 1–3 is Level 1, 4–6 is Level 2, and 7 or above is Level 3. The new abbreviations in that plot are proportional TRC/PH (PTRC) and discrete TRC/PH (DTRC).

The clearest trend in Fig. 7 is the degradation in handling qualities as coupling increases, regardless of response type. The four bars on the left of the figure, representing 0 deg/ft coupling, indicate that pilots overwhelmingly rated that configuration Level 1 regardless of the response type. When the coupling is increased to 2.5 deg/ft the proportion of Level 2 ratings increases for each 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 5 deg/ft all four response types are primarily

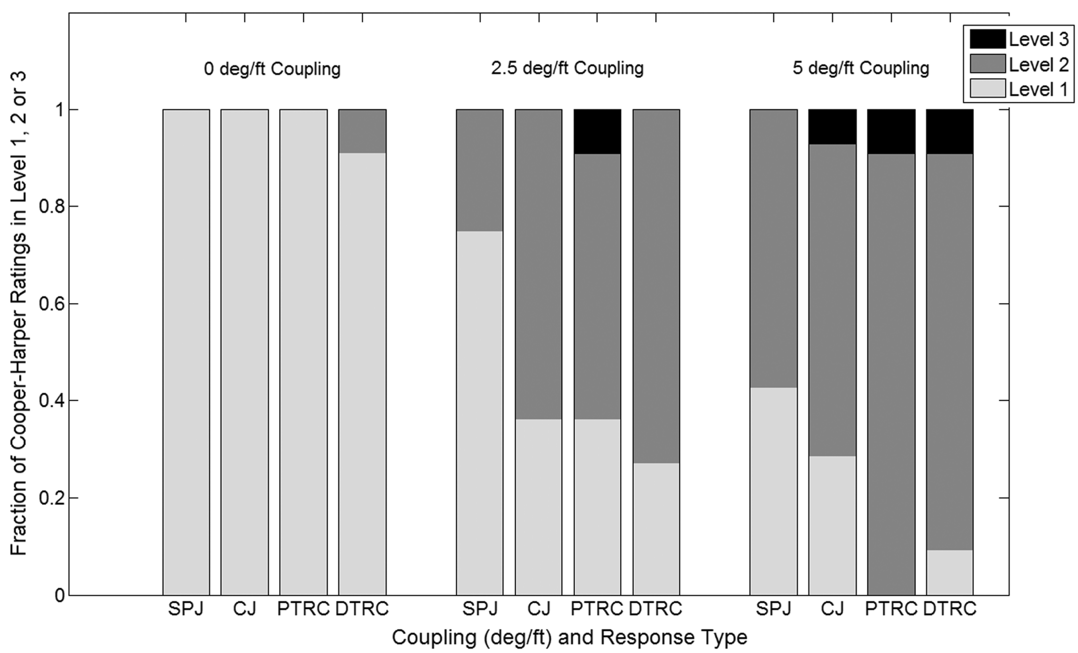



**Fig. 7 Handling qualities levels as a function of coupling and response type.**

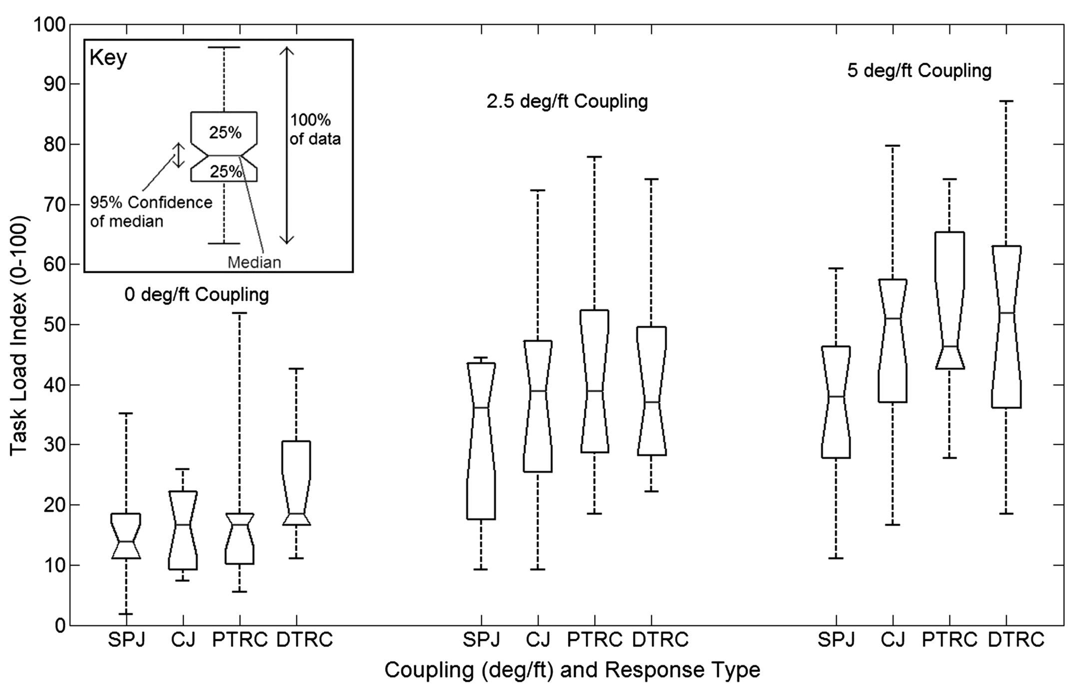



**Fig. 8 Task load index ratings.**

**Table 1 Desired and adequate docking performance bounds**

| Docking parameter | Desired | Adequate |
|---|---|---|
| Radial offset | $\pm 0.125$ ft | $\pm 0.125$ to $\pm 0.267$ ft |
| Roll/pitch/yaw angle | $\pm 2.0$ deg | $\pm 2.0$ to $\pm 3.0$ deg |
| Axial closure rate | 0.075 to 0.125 ft/s | 0 to 0.075 ft/s or 0.125 to 0.15 ft/s |
| Radial closure rate | $\pm 0.0325$ ft/s | $\pm 0.0325$ to $\pm 0.1125$ ft/s |
| Roll/pitch/yaw rate | $\pm 0.05$ deg/s | $\pm 0.05$ to $\pm 0.15$ deg/s |

Level 2. The trend of worsening handling qualities as coupling increases regardless of response type indicates that the degree of coupling is the dominant factor in this handling qualities evaluation.

The TLX rating scale consists of six categories, each of which is rated by pilots to indicate the specific level of workload in that category (e.g., mental, physical, or temporal) and help determine the relative importance of different sources of workload. 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 Fig. 8. The workload ratings results parallel those of the handling qualities ratings (shown in Fig. 7), showing that workload increases significantly when the coupling increases from 0 deg/ft, 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 Fig. 8 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 one may be 95% confident that the medians of the two sets are in fact different; if two notches overlap there is no statistically significant difference between the medians at the 95% confidence level. At that confidence level, all response types in the 0 deg/ft coupling condition were assigned a lower workload rating than any response type in the 2.5 or 5 deg/ft coupling cases. None of the response types in either the 2.5 or 5 deg/ft coupling conditions were statistically different from each other at the 95% confidence level. The clear implication from these plots, as from the CHR plots, 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 deg/ft 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.

The negative result that control system complexity, defined as the degree to which position or velocity are held automatically, does not have a major effect on handling qualities is both surprising and telling. While the previously discussed training issues were certainly a contributing factor to this result, the primary cause is probably the fundamental difference between an orbital docking task and the types of rotorcraft tasks for which these more complex control systems were designed. Orbital docking is accomplished in essentially a disturbance-free environment so that the automatic control system is not removing a significant source of workload for the pilot; the slow orbital mechanics effects are minor in comparison with such disturbances as wind gusts that rotorcraft must contend with. Secondly, a translation rate command system is particularly useful for tasks in which large changes in position are required; however, pilots reported that the difficulty of the docking task was in accurately tracking down the docking centerline rather than in driving the vehicle to the centerline. More specifically, tracking the centerline requires the pilot to distinguish between translation motions and attitude motions, and because the TRC/PH system holds only the former (within a deadband) the pilot receives no assistance in distinguishing these two factors. One solution would be to reduce the size of the attitude deadband so that motion of the docking port within that deadband is a fraction of the docking tolerances, thus giving the pilot knowledge of the held position relative to the target. The historically consistent deadbands used in this experiment resulted in both attitude and translation movements on the order of the docking mechanism tolerances themselves. Finally, as will be discussed in the following section, the propellant used by the different control systems varied widely. Although pilots were explicitly told that propellant was not a factor to consider in rating the handling qualities, principally because these qualitatively different response types naturally use propellant in different quantities, propellant is such a valuable commodity in spaceflight that pilots usually modify their flying technique to minimize its consumption. Such modification results in higher levels of compensation and poorer handling qualities, along with generally less favorable impressions of the performance of that control system. The unexpectedly poor performance of more highly automated control systems suggests that spacecraft handling qualities criteria could be substantially different from those developed for aircraft, and that additional factors may need to be considered by spacecraft designers to ensure good handling qualities.

### B. Docking Performance by Response Type and Degree of Coupling

The CHR 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

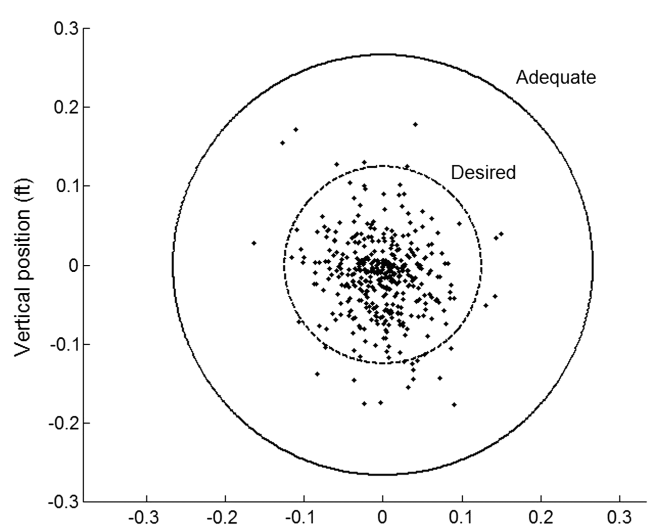



**Fig. 9 Radial offset dispersions ($N = 439$).**

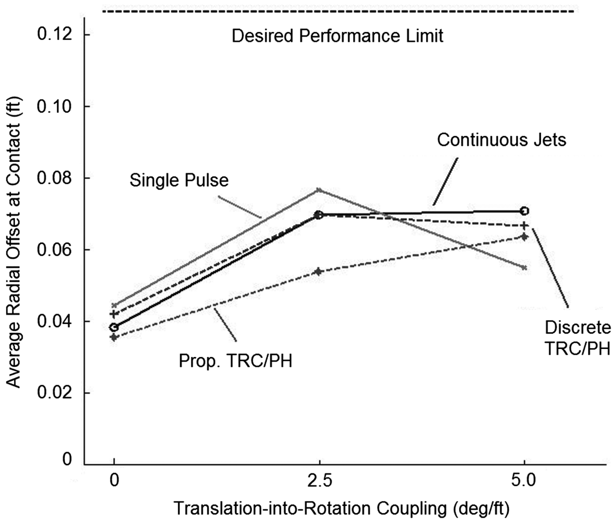



**Fig. 10 Average radial dispersions by response type.**

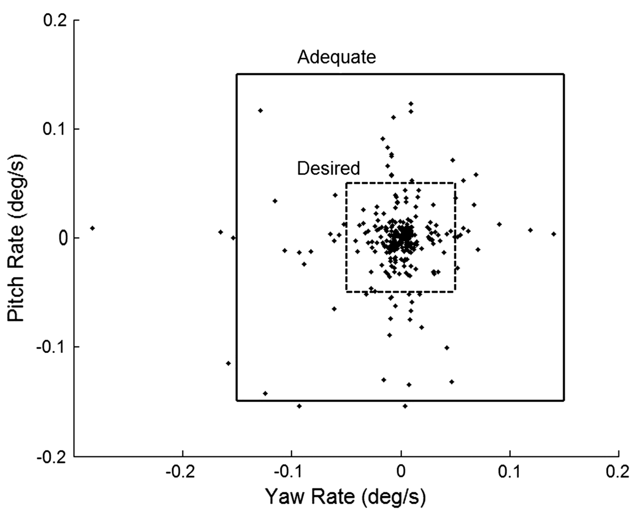



**Fig. 11 Angular velocity dispersion data at contact ($N = 439$).**

performance metrics and, therefore, may be important drivers of overall workload even if the actual performance was always within the desired range. For this task, the adequate docking performance bounds were taken from the structural limits of the APAS (the docking mechanism used by Shuttle) for which a successful docking will occur, and desired performance is approximately twice as accurate as adequate. Although all parameters must be within tolerance to achieve a successful docking, the parameters most relevant to the pilot, and those that were most likely to be outside the desired range, were radial offset and angular rate. The radial offset error is directly observable to the pilot on the centerline camera display, and the angular rates can be well outside adequate if the pilot puts in a translation command just before contact.

The dispersion in the radial offset of all dockings performed during data collection is shown in Fig. 9, along with range rings that define desired (dashed, inner) and adequate (solid, outer) 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 as poor as eight. The average radial offsets achieved as a function of response type and coupling conditions are shown in Fig. 10. 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 deg/ft coupling case and either the 2.5 or 5 deg/ft coupling cases. In general, there is not an appreciable improvement in performance between the 2.5 and 5 deg/ft coupling cases. These results must be qualified by the fact that any radial offset under 0.125 ft is equivalently desirable, and 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 2.5 and 5 deg/ft, 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 deg/ft coupling cases, but that any coupling value at or greater than 2.5 deg/ft results in degraded performance and handling qualities.

The performance parameter that pilots had the most difficulty controlling was the angular velocity; their performance was in the desired range for only 85% of the runs, and in 2% of cases it was outside adequate. The dispersions in yaw and pitch rate are displayed in Fig. 11. Because the docking task in the last 10 ft 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 5 s (roughly 0.5 ft) before docking occurred. Although 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

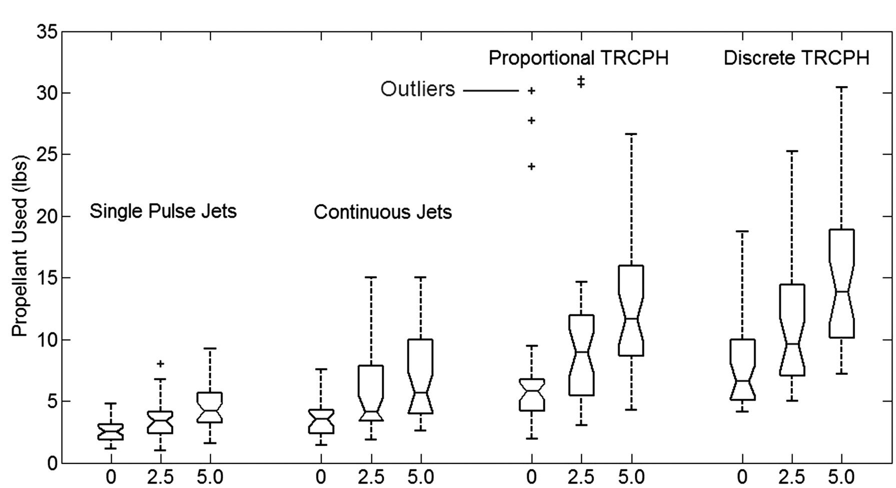



**Fig. 12 Propellant use as a function of response type and coupling.**

measured because minimizing RCS propellant usage is traditionally an important requirement for pilots and, therefore, one that is incorporated into any orbital maneuvering task. However, it was necessary to separate the measurement of handling qualities as a function of response type from that of propellant use, and so the latter factor was excluded from explicit consideration during the evaluations. Box-and-whisker plots of propellant consumed as a function of response type and coupling condition is shown in Fig. 12; outliers are defined as data points that lie more than 1.5 times the interquartile range outside the appropriate quartile. These results mirror those of the 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. In contrast with aircraft, for which normal maneuvering does not have a predominant impact on propellant consumption, good handling qualities for spacecraft may require control systems that conserve propellant resources.

## V. Conclusions

This paper presented the results of a piloted evaluation of handling qualities for the docking of a generic spacecraft with a target docking vehicle. The parameters studied were translation control response type, degree of translation-into-rotation coupling, and the control power (thrust level) of the RCS 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 unwanted angular acceleration that is created when thrusters fire for translational acceleration. Fourteen highly qualified astronauts and test pilots evaluated these configurations on the VMS, a high-fidelity motion simulator at NASA Ames Research Center.

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 deg/ft coupling condition received solidly Level 1 ratings, the 2.5 deg/ft configuration straddled Levels 1 and 2, and the 5 deg/ft 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 that poor end conditions were not responsible for the degraded handling qualities. Rather, the pilot compensation required to overcome coupling to achieve that desired performance causes poor handling qualities; 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 difficulty in compensating for translation-into-rotation coupling using more highly automated control systems is a useful result for spacecraft designers relying on experiences gained from aircraft handling qualities criteria. The amount of propellant consumed by the control system must be considered, and the control system must be designed to compensate for the specific factors that increase workload or degrade performance in a particular task. The quantification of handling qualities as a function of coupling level and control system design presented here should inform the decision about whether to modify these factors to improve handling qualities or whether other factors like pilot display improvements and additional training are sufficient to ensure mission success.

## Acknowledgments

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