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Handling Qualities Evaluation of Pilot Tools for Spacecraft Docking in Earth Orbit

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A piloted simulation was conducted to study handling qualities for the final phase of spacecraft docking in Earth orbit. Twelve evaluation pilots, including 10 pilot astronauts, provided Cooper-Harper ratings, Task Load Index ratings, and qualitative comments. The piloting task was manual translational control with automatic attitude hold during the final 10 ft of docking approach until the docking ports made contact. A previous study established that with conventional translational control, handling qualities for this task degrade significantly as the level of translation-into-rotation coupling increases. The goal of the present study was to evaluate the efficacy of various pilot tools designed to mitigate the handling qualities degradation caused by this coupling. Four pilot tools were evaluated: dead band indicator, flight path marker, translational flight director, and feed forward control. These pilot tools improved handling qualities, generally with greater improvements resulting from using these tools in combination. A key result of this study is that feed forward control effectively counteracts coupling effects while significantly decreasing propellant consumption, providing satisfactory handling qualities for the spacecraft configuration evaluated.

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] They are a manifestation of the interaction between various factors that influence pilot perception of how well (or poorly) a vehicle can be flown to accomplish a desired mission. These factors include the stability and control characteristics of the bare vehicle, the control systems that enhance these characteristics, the inceptors (e.g., control column or throttle lever) used by the pilot to transmit control commands, the visual cues from cockpit windows and displays/instrumentation that provide flight information to the pilot, and other cues (e.g., aural, tactile) that assist the pilot in the execution of the flying task.

The effects of the above factors on handling qualities have been studied in atmospheric flight vehicles over many decades.[2–6] Reference standards for the handling qualities of both fixed-wing aircraft[7] and rotary-wing aircraft[8] 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 to satisfactory, acceptable, and unacceptable handling qualities. Such standards can provide a target for dynamics/control engineers during the design cycle of the vehicle.

At this time, no reference standards exist for spacecraft handling qualities. However, there exists a body of work on handling qualities of piloted spacecraft. During NASA's Gemini and Apollo programs, studies were conducted on spacecraft handling qualities for 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 TV 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

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Apollo vehicles as a function of these parameters.[14,17,19] Those tests showed that for manual control, a rate command with attitude hold (RCAH) mode 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. TV 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 currently being used for Space Shuttle docking operations. The standoff cross and collimated reticle that are Shuttle astronauts' primary means for estimating relative state errors during the final phase of docking were identified during and used in the Apollo program for Crew and Service Module (CSM) docking with the Lunar Module (LM).[18] Several fixed-base[17,19] and six-degrees-of-freedom motion[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 satisfactory.[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 control/display systems that provide desired handling qualities. However, 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.

A new generation of piloted spacecraft is now being designed.[22] These vehicles include the Crew Exploration Vehicle (also known as Orion) to replace the Space Shuttle and ferry astronauts to lunar orbit, and the Altair spacecraft to provide transportation between lunar orbit and the lunar surface. The ability of pilots to successfully carry out their missions will be determined in part by the handling qualities of these new spacecraft. Some flight operations may be fully automated, while others may be executed with a human pilot engaged in various levels of supervisory control including manual flying tasks.[23] It is noted that current NASA procedures require that human-rated spacecraft provide the capability for the crew to manually control the flight path and attitude with satisfactory handling qualities.[24] Even for flight operations that are nominally executed in a highly automated control mode, the control architecture must provide the capability for a human pilot to switch to a manual control mode – whether due to failure of an automated system, or of some component of the spacecraft. In these cases of emergency reversion to manual control, where the pilot role abruptly switches from monitoring to active control, it is important that the vehicle have acceptable 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 appropriate levels of handling qualities are available for both nominal and off-nominal operations.

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. Preliminary studies of lunar landing[25,26] and Earth orbit docking have been conducted.[27,28] This paper reports a follow-on experiment investigating the effect of pilot tools on handling qualities for spacecraft docking in low Earth orbit; specifically, the attenuation of handling qualities degradation arising from translation-into-rotation coupling.

II. Dynamics and Control of Docking Operations

In docking operations, there is an active vehicle (e.g., Space Shuttle) whose trajectory is dynamically controlled to dock with a passive target vehicle (e.g., a Space Station). In this paper, the following terminology is used: Active Docking Vehicle (ADV) and Target Docking Vehicle (TDV). In the simulation used for this work, the TDV was represented by a model of the International Space Station and the ADV was represented by a generic spacecraft whose geometry and maneuvering acceleration properties were derived from an early model of the Orion spacecraft. It is emphasized that the control systems and cockpit displays of the ADV were research prototypes that were developed independently from the Orion Project; details are presented later in the paper.

Prior to docking, a rendezvous maneuver positions the ADV ahead of the TDV with a small closing rate along the orbital velocity vector of the TDV (this is known as the V-bar approach). When the distance between the two docks is about 30 ft, an attitude alignment maneuver is performed to match the attitude of the ADV with that of the TDV, and the final phase of docking (at 0.1 ft/s approach) is executed with the ADV's attitude hold system engaged. The attitude control system fires the ADV's Reaction Control System (RCS) jet thrusters to produce the roll/pitch/yaw moments necessary to hold its attitude within specified dead bands.

A schematic view of the ADV is shown in Fig. 1; note that the docking mechanism is mounted on the nose of the vehicle. A video camera is installed on the nose of the ADV, close to the vehicle centerline. This centerline camera image is displayed to the pilot with a reticle overlay that indicates the center of the ADV docking port using cross-hairs. During final approach for docking, the camera shows the TDV docking port which has various markings, including a circle with a radius of 3 inches drawn around the center of the docking device, as depicted in Fig. 2. A stand-off cross is mounted at the center of the TDV docking port; its dimensions are slightly larger than the circle mentioned above, and it is offset forward a few inches from the surface on which the circle is drawn.

The camera view plus reticle constitutes the minimum pilot tool set required to perform the docking task, enabling the pilot to visually estimate the position and orientation of the ADV docking port center relative to the TDV docking port center. In general, any displacement between the stand-off cross center point and the reticle cross-hairs intersection point reflects a composite of position and attitude errors between the ADV and TDV docking ports. For example, consider a situation where the reticle cross-hairs intersection point is to the right of the TDV docking port center. This could happen if the ADV is displaced to the right of the TDV (translation error), or if the ADV is yawed to the right (attitude error), or a combination of both errors. It is noted that for a successful docking, the radial position error limit must not exceed 3 inches.

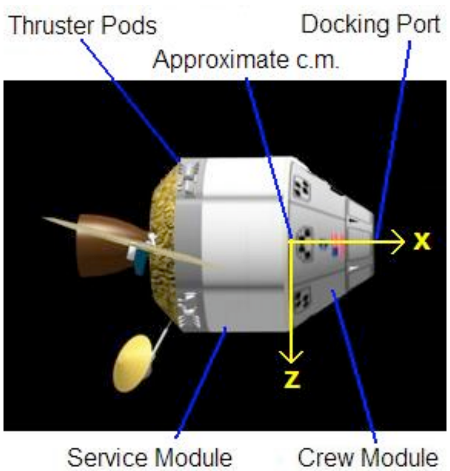

Figure 1. Schematic view of ADV

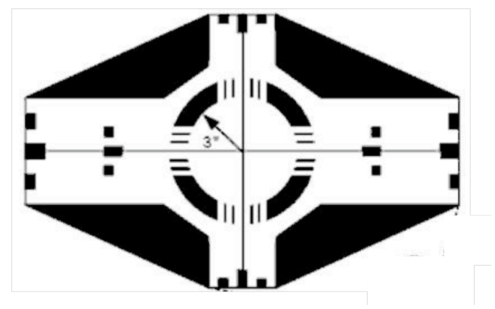

Figure 2. Markings on TDV docking port

The pilot uses a translation hand controller (THC) to make translational control inputs as necessary to null the transverse position error between the center of the ADV docking port and the center of the TDV docking port. This generally requires pilot inputs along two translational axes: up/down inputs to make small trajectory adjustments in the orbital plane along the local vertical, and left/right inputs to make small trajectory adjustments perpendicular to the orbital plane. These inputs fire the appropriate RCS jets to produce the commanded translational motion. For example, the translational control system used for Space Shuttle dockings provides a small change in translational velocity (0.01 ft/s) along the appropriate axis for each discrete input of the THC.

An important aspect of the ADV's dynamics is the degree of coupling from translational inputs into rotational motions. This dynamic coupling arises from the longitudinal offset between the RCS thruster locations and the vehicle center of mass (c.m.), and it results in a thrust coupling between translational and rotational motion that can have a significant impact on handling qualities for docking. The degree of coupling experienced by the pilot is dependent not only on the location of the RCS thrusters relative to the c.m. but also on the control scheme by which forces and moments are generated in response to pilot THC inputs. Coupling is defined in this work as the ratio between the disturbance angular acceleration (deg/s^2) and the applied translational acceleration (ft/s^2) that gives rise to the disturbance; hence the units of coupling are deg/ft.

Consider a vehicle on which the RCS jets are mounted at a significant distance aft of the vehicle c.m. This vehicle is equipped with a conventional translation control system that responds to THC inputs by firing the appropriate RCS jets to create a net thrust force along the appropriate body axis for a pre-calculated time interval to provide a small increment in velocity. For example, a left THC input will produce an RCS thrust force that translates the vehicle to the left, but that force will also induce an unwanted yawing moment that rotates the vehicle's nose to the right. Since the centerline camera is mounted on the nose of the ADV and follows the net motion of the nose (caused by both translation and rotation effects), the pilot may initially perceive a motion in the "wrong" direction until the attitude hold system engages at a dead band limit and counteracts the yawing moment. Although the attitude hold dead bands are quite small (fraction of a degree), the moment arm from vehicle c.m. to nose results in an equivalent translational nose motion of the order on an inch, which is near the level of accuracy required for successful docking.

III. Pilot Tools for Docking

A prior study[27] of docking operations found that translation-into-rotation coupling can significantly degrade handling qualities. Specifically, it was determined that a coupling level of 5 deg/ft results in handling qualities deficiencies that warrant improvement. In the current study, pilot tools were developed with the goal of improving handling qualities in the presence of substantial translation-into-rotation coupling. These tools are described below.

Dead Band Indicator (DBI)

A previous experiment[27] revealed that a key factor in pilot compensation was predicting when the attitude hold system would hit a dead band limit and automatically fire RCS jets to create a counteracting moment. For example, consider a scenario just before docking port contact where the reticle indicates a near-zero position error between the centers of the two docks. In actuality, the ADV has a yaw error on the right dead band limit and a substantial translation error to the left which effectively cancel each other. Momentarily, the yaw error exceeds the dead band limit and the attitude hold system fires RCS jets to compensate. The yaw error is quickly attenuated while the translation error persists when the docking ports make contact a few seconds later. Due to this substantial position error, the docking mechanisms do not latch together and the docking attempt is unsuccessful. Knowledge of the docking port position error decomposition into translation and attitude error components would help the pilot make appropriate decisions about THC inputs.

Figure 3a shows a square box around the reticle cross-hairs. This attitude dead band box indicates the ADV pitch and yaw attitude error magnitudes relative to the attitude hold dead bands. It is noted that these attitude errors are referenced to the nominal attitude hold values established by the attitude alignment maneuver prior to final docking approach. If the center of the box coincides with the cross-hair intersection then the yaw and pitch errors are zero; if a side of the box lies along a cross-hair then the corresponding attitude error is at a dead band limit. The illustration in Fig. 3a indicates that the ADV is pitched down and yawed right, and that these attitude errors are roughly 50% of the attitude dead band limit.

Flight Path Marker (FPM)

The aircraft-like symbol in Fig. 3a is a conventional representation of a flight path marker. Its position is derived from the translational velocity of the ADV c.m. relative to the TDV c.m., projected linearly from the ADV's docking port center. The illustration in Fig. 3a indicates that if the current relative velocity were to persist, the ADV's docking port center would make contact below and to the right of the TDV's docking port center. Figure 4 shows the projections of the reticle cross-hairs and flight path marker on the plane of the TDV's dock.

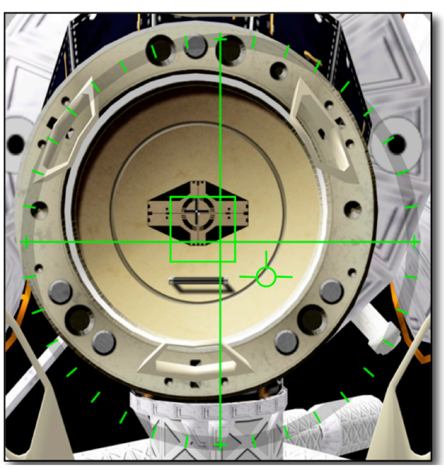

Figure 3a. Dead band indicator and flight path marker

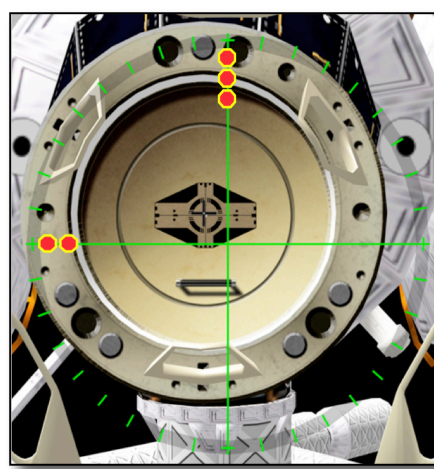

Figure 3b. Translational flight director

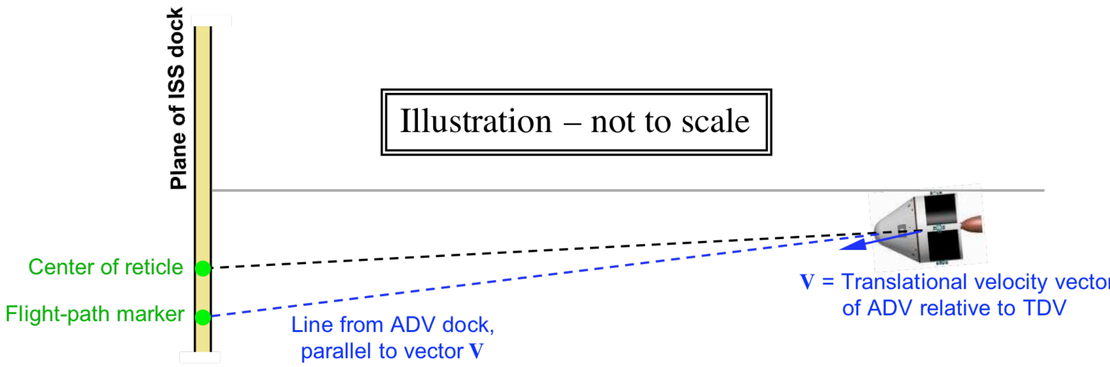

Figure 4. Details of reticle and flight path marker

Translational Flight Director (TFD)

The number and directionality (right/left and up/down) of THC inputs required for a successful docking are indicated by red dots superimposed on the reticle. The illustration in Fig. 3b indicates that the pilot should make three THC inputs upwards and two inputs to the left. The guidance algorithm is a state feedback law that has two phases. The goal of the first phase is to eliminate any transverse offsets by zeroing out the radial position error and radial velocity before the axial distance between the two docking ports drops below 3 ft. The second phase provides fine tuning to compensate for drift by minimizing the projected radial position error at docking port contact.

Feed Forward Control (FFC)

The conventional type of compensatory attitude control employs feedback and is reactive in nature. For example, consider a THC input commanding a left-pointing force behind the vehicle c.m.; this force will create a nose-right yaw error due to translation-into-rotation coupling. In a feedback attitude hold control system, RCS jet firings to create a nose-left yawing moment are commanded only after the yaw error increases to a value that exceeds a specified dead band limit.

A feed forward control system is proactive in nature. In the example above, a feed forward control system would estimate the undesired nose-right yawing moment that would arise from a left THC input, and fire RCS jets simultaneously to provide a left-pointing force as well as a nose-left yawing moment that cancels out the translation-into-rotation coupling effect. In practice, the coupling effect is not completely cancelled but is greatly attenuated. The operation of the feed forward control system is transparent to the pilot; the vehicle responds as if it had very low translation-into-rotation coupling.

A convex optimization software package in MATLAB® was employed to directly select, subject to propellant considerations, optimum RCS jet firing times to cancel the angular rates arising from coupling effects in response to translation commands. The algorithm also accounted for some operational limitations of RCS jets. The minimum on-time for a jet is 40 ms so there is a small but finite minimum angular (or translational) impulse that can be achieved; in addition, the jet firing times need to be discretized (rounded) to 10 ms. For these reasons, and because the jets are not all pointed symmetrically about the c.m. and paired in couples, attenuating translation-into-rotation along one axis also creates a small amount of coupling into the other two axes. Errors in estimates of vehicle mass/inertia properties and actual RCS jet thrust will also result in small residual coupling effects, although such errors were not modeled in this simulation.

The cost function J employed in calculating firing times for the feed forward system was:

$$J = \left\| \boldsymbol{A}\,\Delta t - \Delta v_{target} \right\|_1 + \mu \sum_i \left[\Delta t_i \right]$$

In the equation above, $\boldsymbol{A}$ is the matrix of vehicle translational and rotational accelerations resulting from the firing of each jet, Δt is the vector of firing times for all jets, and their product represents the resulting translational and rotational velocity components. Δv_{target} is the set of three translational velocity components (target values commanded by THC inputs) and three angular velocity components (target values of zero) that the jet firing is trying to achieve. The resulting difference vector is reduced to a scalar using the 1-norm (which simply sums the absolute values of each of the vector components), and this quantity is a measure of the precision with which the target velocity components are met. The parameter μ is a weighting factor that trades the relative importance of propellant usage (which is directly proportional to jet firing time) against the precision with which the target velocity components are met, and i is an index representing each RCS jet.

The optimization program was run for a wide range of values of the weighting factor, μ, and the firing time constraints discussed previously were then applied to calculate the resulting velocity components; the set of firing times that resulted in the lowest value of the maximum of the three angular velocity components was then selected. This process was done for each of the four pertinent THC inputs (left, right, up, down) by proper choice of the vector Δv_{target}, and the resulting jet firing times were stored and recalled for use as necessary. It was determined through analysis that this implementation of feed forward attenuates translation-into-rotation coupling by a factor of at least 50 relative to the baseline of no feed forward control.

IV. Experiment Design

The principal objective of this experiment was to evaluate the effect of various pilot tools on spacecraft handling qualities for Earth orbit docking. This section describes various aspects of the experiment design.

Flying Task

The task selected was the final phase of docking operations during which the ADV approached the TDV along its orbital velocity vector (this is known as the V-bar approach). In this experiment, the TDV was in a circular orbit 217 miles above the surface of the Earth, and it experienced no perturbations in position or attitude during the simulation run. At the start of the simulation run, the ADV was in essentially the same orbit as the TDV and was positioned slightly ahead of the TDV with the ADV's nose pointed along its negative orbital velocity vector. The axial distance between the ADV and TDV docking ports was 10 ft and the relative axial closing speed was 0.1 fps, resulting in a nominal run time of 100 sec.

In order to provide sufficient piloting challenge and expose any handling qualities issues, a radial offset error was applied to the initial position of the ADV docking port relative to the TDV docking port. This resulted in two piloting subtasks: (1) make coarse trajectory changes to align the centerline of the ADV docking port with the centerline of the TDV docking port, and (2) make fine trajectory changes as necessary to maintain this alignment. In order to compare the levels of pilot compensation for these subtasks, two types of approaches were designed: offset and nominal. The offset approach began with a large (operationally unlikely) radial offset error of about 4.25 ft, while the nominal approach began with a small (operationally likely) radial offset error of about 0.5 ft.

Experiment Matrix

The primary objective of this experiment was to evaluate the effect of various pilot tools, individually and in selected combinations, on spacecraft handling qualities for Earth orbit docking. Secondary objectives were to evaluate the effects of attitude hold dead band size and the magnitude of initial position errors (nominal vs. offset approach) on handling qualities for Earth orbit docking. The experiment matrix is depicted in Figure 5.

Pilot Tools* → **Run type** ↓	None	Dead Band Indicator (DBI)	Flight Path Marker (FPM)	DBI + FPM	Translational Flight Director (TFD)	TFD + DBI + FPM	Feed Forward Control (FFC)	FFC + DBI + FPM
Offset approach; 0.25 deg dead-band								
Nominal approach; 0.25 deg dead-band								
Nominal approach; 0.5 deg dead-band								

*** In addition to reticle, which is displayed for all pilot tool configurations**

Figure 5. Experiment matrix

Evaluation Pilots

12 experienced test pilots provided data for this experiment; they had an average of 6,500 flight hours in a variety of fixed/rotary wing aircraft. Two were NASA pilots with decades of aircraft flight test/simulation experience. The other 10 were current/retired NASA pilot astronauts from the Space Shuttle program; they had flown a total of 11 missions as Pilot and eight missions as Commander. Many of the astronauts had performed actual spacecraft dockings, and most of them had received extensive simulator training on rendezvous/docking operations. Each pilot was available to the experimenters for about 8 hours, and this time constraint was incorporated into the experiment design.

Training Procedures

Upon arrival, pilots received a detailed briefing on the experiment background and objectives, flying task, control system, test matrix, and data collection procedures. Including discussion time with the experimenters, this session lasted approximately one hour. This was followed by a training and familiarization session (about one hour) in the simulator cockpit, where pilots practiced the flying task for various representative configurations drawn from the test matrix, until they felt comfortable that most of the learning curve was behind them.

Data Collection Procedures

Each pilot encountered the various experiment configurations in a different sequence, and was not told the value of the attitude hold dead band and whether the feed forward control system was on. For each test configuration, the pilot flew two formal evaluation runs with an option for a third run if necessary (e.g., significant difference in docking performance across the first two runs).

In handling qualities experiments, pilots are generally asked to make a composite assessment of the overall performance across all formal evaluation runs for a test configuration. It is important to note that this assessment takes into account not just the quantitative evaluation of the end point (e.g., docking contact) performance but also a qualitative evaluation of the manner in which the vehicle gets to the end-point. This overall assessment of desired, adequate, or inadequate performance is utilized for walking through the decision tree in the Cooper-Harper chart.[1] Pilots use the Cooper-Harper scale to assign handling qualities ratings from 1 (best) to 10 (worst) based on their assessment of task performance and effort. It is an ordinal scale, which means for example that the difference between ratings of 1 and 2 is not the same as the difference between ratings of 3 and 4. Ratings of 1, 2, and 3 on the Cooper-Harper scale correspond to Level 1 handling qualities, which are a general requirement for normal operations of flight vehicles. Ratings of 4, 5, and 6 correspond to Level 2 which may be acceptable for some off-nominal conditions, and ratings of 7, 8, and 9 correspond to Level 3 which is acceptable only for transition to a safe mode after a major failure/disturbance. Desired performance is necessary (but not sufficient) for Level 1 ratings, and adequate performance is necessary (but not sufficient) for Level 2 ratings.

	Desired	Adequate
Radial Misalignment	1.5 in	3.2 in
Angular Misalignment	Roll: ±1.5 deg Pitch/Yaw: 1.5 deg (vector sum)	Roll: ±3.0 deg Pitch/Yaw: 3 deg (vector sum)
Axial Closure Rate	0.075 to 0.125 fps	0.05 to 0.15 fps
Radial Closure Rate (combined translational and rotational rates)	0.075 fps	0.15 fps
Relative Angular Rate	±0.075 deg/sec (each axis)	±0.15 deg/sec (each axis)

Figure 6. Limits of docking contact performance parameters

At the end of each run, relevant docking contact performance parameters (see Figure 6) were displayed to the pilot and experimenters, with values colored green, orange, and red according to performance limits for docking contact. The values of adequate performance bounds for the parameters were derived from structural limits for the docking mechanisms; desired performance limits were established by eliminating approximately half the tolerances for adequate performance.

After making a composite assessment of the overall performance across the formal evaluation runs for a test configuration, pilots walked through the Cooper-Harper chart and assigned a handling qualities rating for that test configuration. Next, they assigned ratings for each of the six components of the NASA Task Load Index.[29] These six components were: physical demand, mental demand, temporal demand, performance, effort, and frustration. The relative weighting of these six components for the docking task was determined by a pilot questionnaire at the end of the experiment. As appropriate, pilots also made qualitative comments about the test configuration they had just evaluated. All pilot comments were recorded on electronic media; the experimenters noted key points.

After all test configurations had been evaluated, there was a debrief session. The pilots were asked to fill out a one-page questionnaire designed to elicit high-level comments on cockpit displays, out-the-window displays, guidance cues, control response, and experiment design. This was followed by a discussion with the experimenters.

V. Simulation Environment

The experiment was conducted on the Vertical Motion Simulator (VMS) at the NASA Ames Research Center. The VMS is a large motion base simulator[30] that has been used for numerous handling qualities evaluations.[31] Six-degree-of-freedom simulator motion was utilized for the experiment, although the motion cues for this task were very subtle. A single pilot seat was installed in the center of the simulator cab, with a researcher/observer seat immediately aft of the pilot seat. A three-axis translational hand controller (THC) was installed on the left side of the pilot seat. Although a three-axis rotational hand controller (RHC) was installed on the right side of the pilot seat, it was not used in this experiment, consistent with current operating procedure in the final phase of docking. A schematic of the cockpit layout including the two control inceptors is shown in Fig. 7.

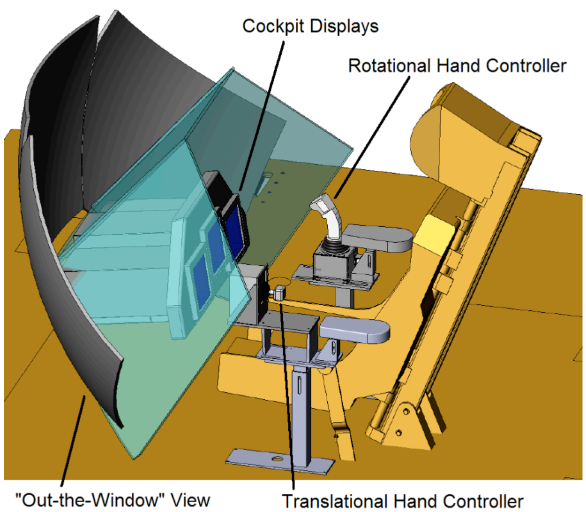

Figure 7. Simulator cockpit layout

A simulated view of the TDV (represented by a model of the International Space Station) was projected on a set of three wide angle collimated color displays. The image resolution was 1/2 pixel per arcmin, corresponding to approximately 20/40 visual acuity. The window display had a large field of view: 48 deg vertical and 120 deg horizontal. Window masking was not used in the simulator cockpit and therefore the entire field of view was available to the pilot. This is not representative of actual operations where the pilots have only a limited field of view through small windows. However, the docking task in this experiment was essentially a head-down task, and the pilot's attention was focused primarily on the cockpit instrumentation rather than the view outside the cockpit.

The cockpit console had three 6.5-inch color flat panel displays, the contents of which are shown in Fig. 8. The center panel displayed a simulated view from a camera mounted on the centerline of the ADV dock, with a green reticle (cross-hairs) overlay; additional pilot tools were overlaid on this display as appropriate for the test configuration. It is noted that the TDV docking port is the beige ring with numerous holes and three petal-like objects in the center of this display. The right panel displayed an Attitude Director Indicator (ADI) and tapes showing range and range rate of the ADV's docking port relative to the TDV's docking port. The left panel displayed color coded end-of-run data on several performance parameters at docking port contact, such as radial offset error and relative angular rates; this panel was blank during the run. Pilots primarily used the center panel display to perform the assigned docking task.

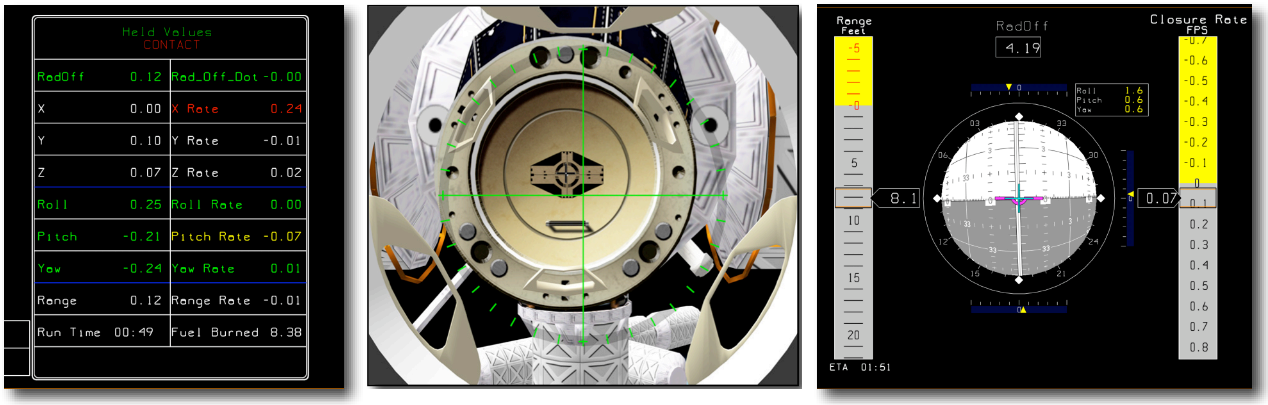

Figure 8. Cockpit displays

Dynamics and Control Model

A dynamics and control model was implemented in the VMS, as described below. The translational and rotational motion of the spacecraft, including primary orbital mechanics effects, was modeled using the flight dynamics model described in Ref. 27. It is noted that the full equations of motion for both the ADV and TDV were modeled separately, rather than using an approximate model for the dynamics of relative orbital motion.

An ADV model was developed for this experiment using Orion vehicle configuration information available at the time. That design information included the RCS thruster locations, vehicle dimensions, mass properties and some other pertinent details, but did not include control system or cockpit display designs. Research prototype control systems and cockpit displays were independently developed for this experiment. For the baseline (no tools) configuration, the level of translation-into-rotation coupling was 5 deg/ft.

The docking task in this experiment used only the "attitude and translation" RCS jets; neither the auxiliary thrusters nor the additional RCS jets used for Command Module re-entry were modeled. The jets of interest are located in four groupings, or quads, around the circumference of the Service Module, towards the aft end of the spacecraft. Each quad consists of four jets, two angled forward and two angled towards the rear, for a total of 16 RCS jets. The jets are further divided into two redundant strings (A and B) consisting of eight jets each. The dynamics model of each RCS jet included a time delay, a minimum firing duration, and a minimum time interval between sequential firings.

The control response type in the translation axes corresponded to a discrete velocity increment mode. Displacement of the THC out of detent commands the appropriate RCS thrusters to fire for a pre-calculated duration, resulting in a fixed velocity increment (0.01 fps); the THC must be returned to detent before another command can be issued. This response type is similar to that used by the Space Shuttle during docking operations. It was also the highest-rated translational control response type in the previous handling qualities study.[27]

The control response type in the rotational axes was Rate Command / Attitude Hold (RCAH). It is noted that pilots were instructed not to make any rotational control inputs, and hence the rotational control system was always in attitude hold mode. Phase-plane switching curves were used to hold attitude (see Fig. 9). In that figure, the switching curves represent the edges of a dead band within which the RCS jets do not fire.

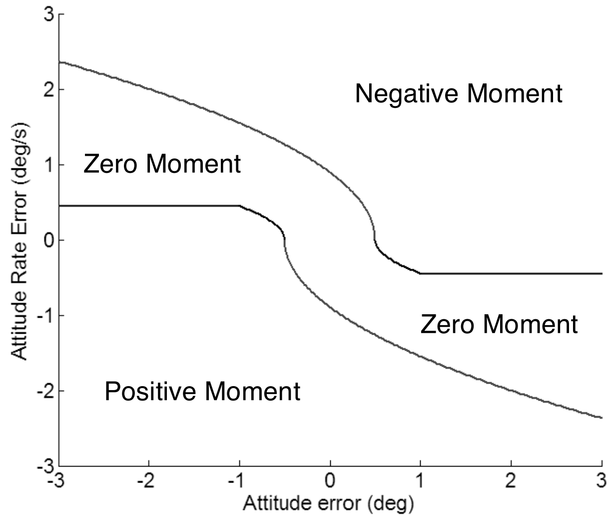

Figure 9. Switching curves for pitch attitude hold with 0.5 deg dead band

RCS firings generated by the attitude hold logic were assigned higher priority, in order of pitch, then yaw, then roll; THC commands received lower priority. THC commands not allocated to an RCS string were placed in a command queue, awaiting allocation as soon as a string became available and there were no higher-priority commands in the queue. When a string became available at the THC priority level, the first THC command in the queue was converted into RCS jet firing times and allocated to the string. The lookup table used for conversion of THC commands into RCS jet firing times was determined by the THC mode selected – either basic or feed forward control. In theory, the two RCS jet strings could become saturated with commands. In practice, for the runs during this experiment, there were almost no instances where a pilot's THC command was noticeably "queued" (and therefore delayed).

VI. Results

The formal evaluation period in the VMS was May 27 through June 13, 2008. The 12 evaluation pilots provided Cooper-Harper ratings, NASA Task Load Index (TLX) ratings, and specific comments for each of the experiment configurations. They also provided feedback on the experiment design, as well as their overall impressions of the docking task. For each run, time histories of numerous simulation variables were recorded along with key performance parameters at docking port contact. A total of 617 formal evaluation runs were made during this experiment. This section presents the qualitative and quantitative results obtained from these runs.

Handling Qualities Ratings

Figures 10 and 11 show color coded Cooper-Harper rating data for various pilot tools, individually and for the combinations evaluated in this experiment; in Fig. 10 the paired bars enable a comparison across 0.25 and 0.5 deg dead bands for the nominal approach, while in Fig. 11 the paired bars enable a comparison across nominal and offset approaches for a 0.25 deg dead band. It is noted that the reticle was present for all pilot tool configurations. As an example, the left-most bar in Fig. 10 indicates that for the test configuration of no tools and offset approach, about 40% of the pilots gave a Level 1 rating, about 60% gave a Level 2 rating, and there were no Level 3 ratings.

Figure 10 shows that the 0.25 deg dead band significantly improves handling qualities relative to the 0.5 deg dead band, for all pilot tool configurations without feed forward control. For a fixed value of dead band, the use of pilot tools improves handling qualities relative to the corresponding baseline of no tools (i.e., reticle only). The extent of improvement depends on the tool(s). It can be seen that the two configurations with feed forward control are the only ones that received a Level 1 rating from virtually all pilots, and correspond to the pilot tool configurations with the best handling qualities. The dead band indicator, flight path marker, and translational flight director each provide a modest improvement in handling qualities. The combination of dead band indicator and flight path marker received good ratings as well as favorable pilot comments. Providing dead band indicator and flight path marker in addition to feed forward control did not make any significant difference.

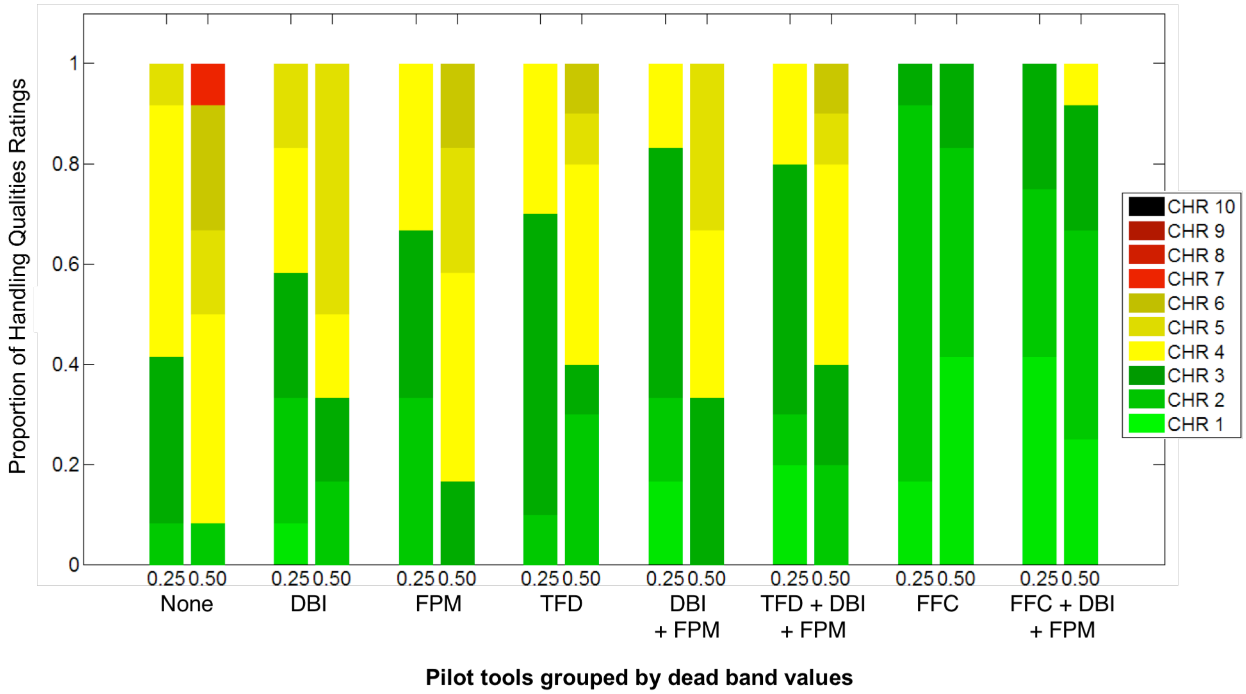

Figure 10. Handling qualities ratings for nominal approach, 0.25 and 0.5 deg dead bands

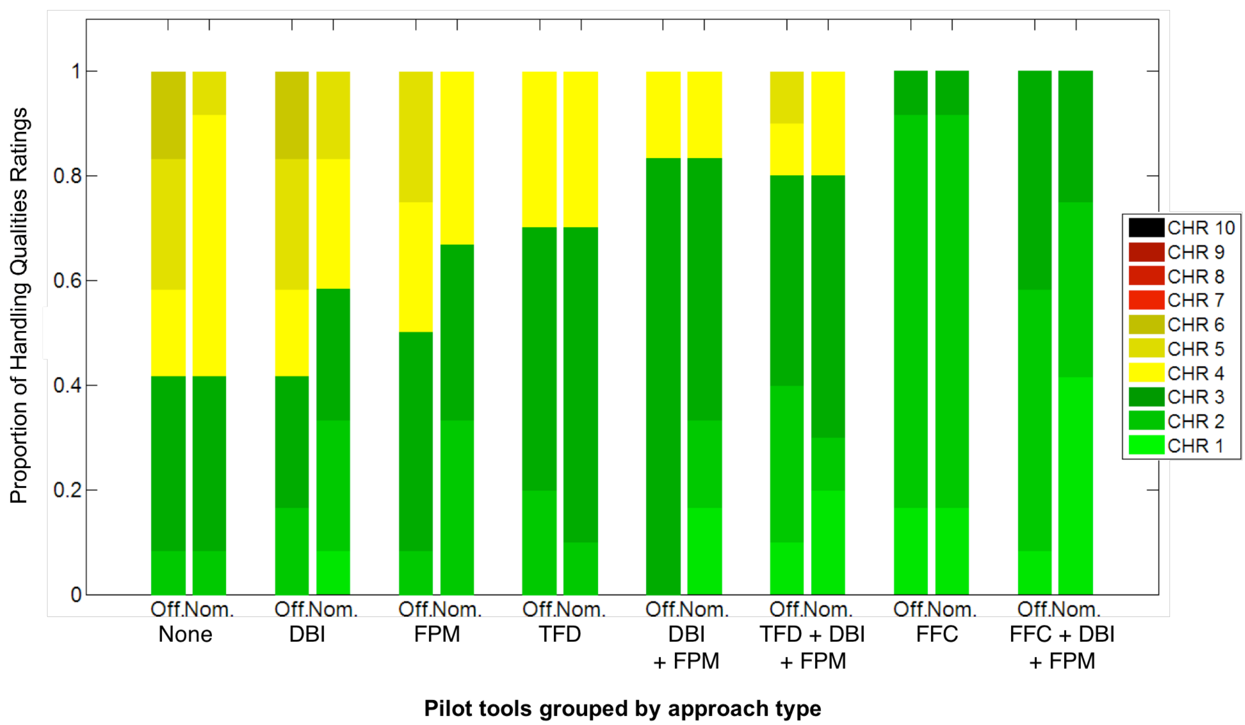

Figure 11. Handling qualities ratings for 0.25 deg dead band, offset and nominal approaches

The docking task in this experiment had two piloting subtasks: (1) make coarse trajectory changes to align the centerline of the ADV's docking port with the centerline of the TDV's docking port, and (2) make fine trajectory changes as necessary to maintain this alignment. The first sub-task was significant for the offset approach and negligible for the nominal approach, while the second subtask was essentially the same for both the offset and nominal approaches. Figure 11 shows similar handling qualities for nominal and offset approaches, regardless of pilot tool configuration. This indicates that the second subtask, making fine trajectory changes to maintain alignment between the two docking ports, is the dominant one for the overall docking task.

Task Load Index Ratings

Figure 12 shows NASA Task Load Index component ratings (averaged across all pilots) for selected pilot tools: dead band indicator, dead band indicator plus flight path marker, and feed forward control. It is noted that the reticle was present for all pilot tool configurations. There are two sets of data shown in Fig. 12, corresponding to 0.25 and 0.5 deg attitude hold dead bands.

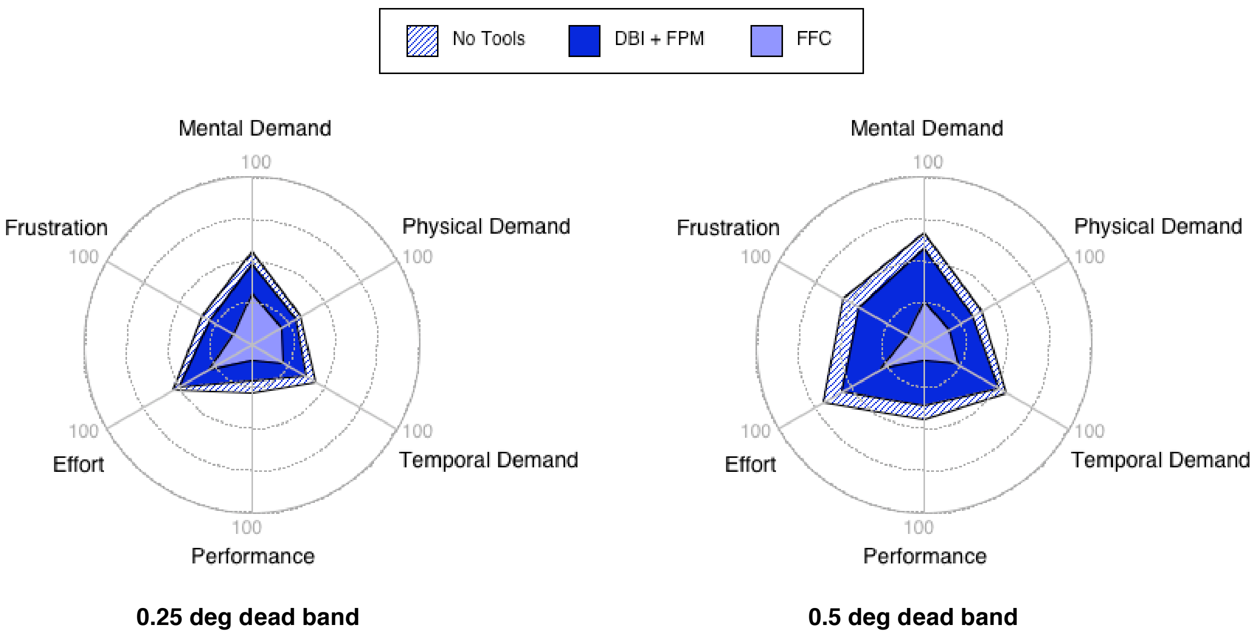

Figure 12. Task Load Index component ratings for selected pilot tools; nominal approach

It is evident that the smaller (0.25 deg) dead band significantly decreases all task load components, for all tool configurations without feed forward control. For a fixed value of dead band, the use of pilot tools provides some reduction in workload relative to the baseline of no tools (i.e., reticle only). The extent of improvement depends on the tool(s). Relative to the baseline of no tools (i.e., reticle only), the combination of dead band indicator and flight path marker provides a modest reduction in pilot task load while feed forward control provides a significant reduction in pilot task load. It can be seen that the primary TLX components for this flying task are mental demand, temporal demand, and effort, while the secondary components are physical demand, performance and frustration.

Propellant Usage

Figure 13 shows the average propellant consumed per docking (nominal approach) for various pilot tools, individually and for the combinations evaluated in this experiment. It can be seen that the propellant usage with feed forward control is lower than that of pilot tool configurations without feed forward control, indicating that feed forward control improves handling qualities while decreasing propellant usage. With feed forward control, the reduction in propellant usage relative to the baseline (no tools) configuration is 25% for the 0.25 deg dead band case and 43% for the 0.5 dead band case.

Although each THC input with feed forward control on increases propellant usage by an average of about 50% (relative to feed forward control off), the more predictable nature of the resulting trajectory requires fewer adjustments by the pilot (i.e., fewer THC inputs) and less bouncing across dead bands between THC inputs. Consequently, the overall propellant usage is less.

It can also be seen that for each pilot tool configuration, there is generally a significant reduction in propellant usage across the 0.25 and 0.5 deg attitude hold dead bands, although in some configurations there is neither a significant increase or decrease. For the baseline (no tools) configuration, the propellant usage for the 0.25 deg dead band case is 24% less than that for the 0.5 deg dead band case.

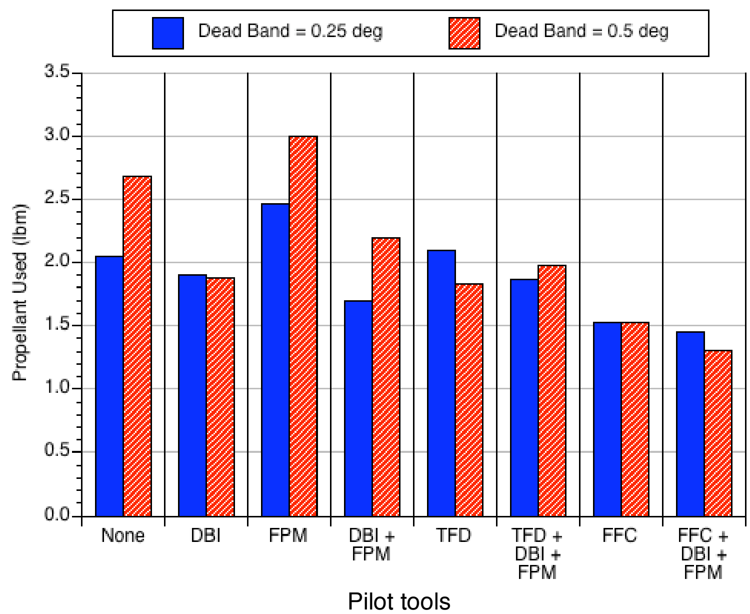

Figure 13. Propellant usage for various pilot tools; nominal approach

Docking Performance

The various parameters for docking performance are given in Fig. 6. Radial misalignment is the principal parameter of interest. Position errors at docking port contact (soft dock) are shown in Figure 14. The smaller (green) circle represents the error bound for desired performance (1.5 in) and the larger (red) circle represents the error bound for adequate performance (3.2 in).

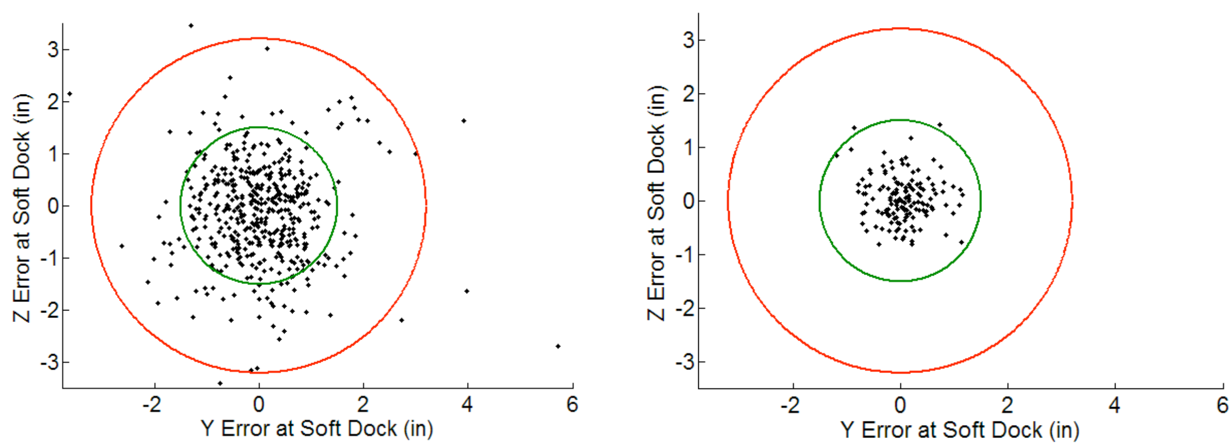

Figure 14. Docking position errors for feed forward control off (left) and feed forward control on (right)

It was determined that 99% of the 617 formal evaluation dockings were within the bound of adequate performance for position error. For configurations without feed forward control (left plot), 80% were within the desired performance bound for position error. This indicates that even for configurations without feed forward control, pilots were generally able to achieve the desired level of performance and the Level 2 handling qualities ratings can be attributed to the substantial level of pilot compensation necessary to achieve that performance. Feed forward control improved docking performance: it was found that 99% of such dockings (right plot) were within the desired performance bound for position error.

VII. Conclusions

An evaluation of handling qualities for spacecraft docking in Earth orbit was conducted by 12 pilots, including 10 astronauts, flying the NASA Ames Vertical Motion Simulator. The objective was to study the effects of various pilot tools on handling qualities of a spacecraft with significant translation-into-rotation coupling, for the task of translational control during the final phase of docking. Four pilot tools were designed with the goal of enhancing handling qualities: dead band indicator, flight path marker, translational flight director, and feed forward control. Handling qualities with these tools, individually and in selected combinations, were compared to a baseline no-tools configuration.

The baseline no-tools configuration had unsatisfactory handling qualities due to the effects of translation-into-rotation coupling; about 40% of the pilots gave it a Level 1 rating while the remainder (about 60%) gave it a Level 2 rating. Use of dead band indicator, flight path marker, and translational flight director, individually and in selected combinations, improved handling qualities but did not make them solidly Level 1. Utilizing feed forward control yielded a substantial improvement in handling qualities (virtually all ratings were Level 1) while reducing propellant usage.

For pilot tool configurations that did not use feed forward control, it was found that a lower dead band for attitude hold (0.25 deg vs. 0.5 deg) substantially improved handling qualities while generally reducing propellant usage. It was also found that the sub-task of making fine trajectory changes to maintain alignment between the two docking ports dominates the overall docking task during final approach.

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