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CONTROL REQUIREMENTS TO SUPPORT MANUAL PILOTING CAPABILITY

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The manual piloting requirements specified under the NASA Constellation Program involved Cooper-Harper ratings, which are a qualitative and subjective evaluation from experienced pilots. This type of verification entails a significant investment of resources to assess a completed design and is not one that can easily or meaningfully be applied upfront in the design phase. The evolution of the Multi-Purpose Crew Vehicle Program to include an independently developed propulsion system from an international partner makes application of Cooper-Harper based design requirements inadequate.

To mitigate this issue, a novel solution was developed to reformulate the necessary piloting capability into quantifiable requirements. A trio of requirements was designed which specify control authority, precision, and impulse residuals enabling propulsion design within specified guidance and control boundaries. These requirements have been evaluated against both the existing Orion design and the proposed ESA design and have been found to achieve the desired specificity. The requirement set is capable of being applied to the development of other spacecraft in support of manual piloting.

INTRODUCTION

In the course of human spaceflight, the ability to rendezvous and dock two free-flying vehicles have been critical functions necessary to complete missions such as lunar landings and the construction of the International Space Station. Early crewed space missions lacked the need and vehicles lacked the capability in sensors and computing to perform such tasks autonomously and, as a result, manual piloting by the astronauts on board was necessary. While future space missions require and modern technology

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enables both manual and autonomous rendezvous and docking, these delicate operations remain a driver for vehicle control systems.

The Orion Multi-Purpose Crew Vehicle (MPCV) Program continues in the need to develop both automated and manual piloting capabilities that certain mission may require. The broad scope of potential MPCV missions includes Rendezvous, Proximity Operations, and Docking (RPOD) operations with various targets vehicles, such as, habitation modules or lunar landers. The ability to control the spacecraft to precise tolerances is necessitated by the low impact docking system design anticipated for future vehicles. Further, the ability to perform manual control requires a spacecraft control system with rotational and translational control considerations that allow the pilot to correctly apply the appropriate inputs. Whereas traditional integrated performance and Cooper-Harper rating requirements could specify this performance capability, these cannot be ascribed to a standalone propulsion system since their evaluation would not be possible without the corresponding GNC software and logic. The incorporation of an International Partner to the MPCV Program created just such a division of responsibility that had to be resolved through an innovative approach to the piloting requirements.

MANUAL PILOTING CAPABILITIES

Since the dawn of aviation, ease of control for the pilot has been a concern. This concern manifests because, if an otherwise flight worthy aircraft has difficult or confusing pilot controls, the risk of injury or damage is significantly higher. Developed in 1969, the Cooper-Harper rating system has been used by the aviation industry to ascribe a value to the experience of the pilot during aircraft operation. The scale[1] ranges from 1 to 10, where 1 is the best and 10 is the worst as depicted in Figure 1. Further, the ratings are grouped into levels such that ratings 1, 2, and 3, are considered “level 1”, 4, 5, and 6, are “level 2”, and 7, 8, and 9 are “level 3”. To determine a Cooper-Harper rating, a pilot or series of pilots fly the vehicle or simulations and then provide their qualitative score based on the criteria given.

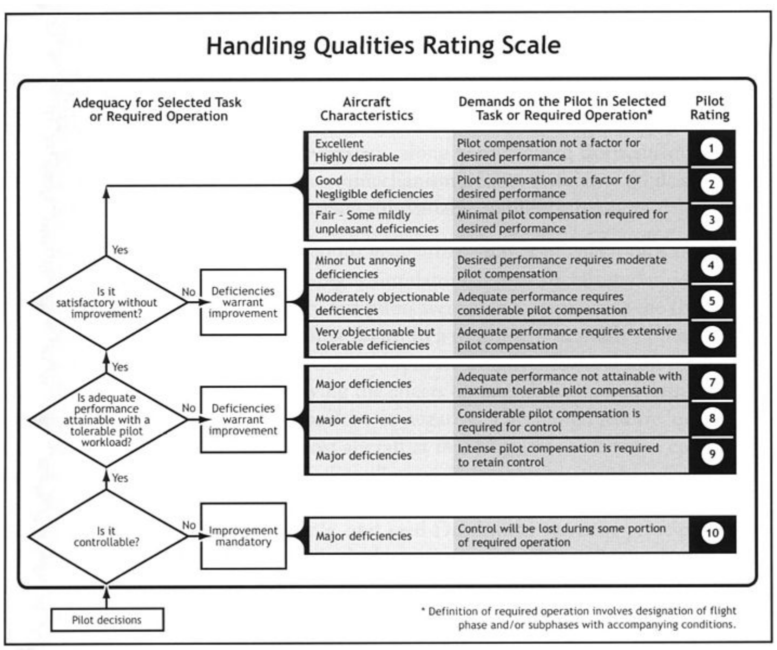

Figure 1 Cooper-Harper Rating Scale

The ability to assess a Cooper-Harper rating is dependent on many factors of the vehicle design including the control system, piloting controls and displays, visual capability, and others. These are all highly integrated and require a certain amount of system maturity to support a handling quality assessment. If an insufficient score is found, iterative development is needed to fix deficiencies identified by the pilot(s) and follow on assessments would be needed.

For the MPCV, a level 1 Cooper-Harper rating requirement was incorporated early in the vehicle definition. To support the desirable piloting experience, significant effort was applied to ensure that the control system, propulsion system, and related items such as the windows, cockpit displays, and hand controllers were developed with the pilot in mind. Rapid prototype laboratories, such as the Reconfigurable Operational Cockpit shown in Figure 2, were established integrating early versions of this hardware and software to support manual piloting assessments by astronauts during RPOD simulations.

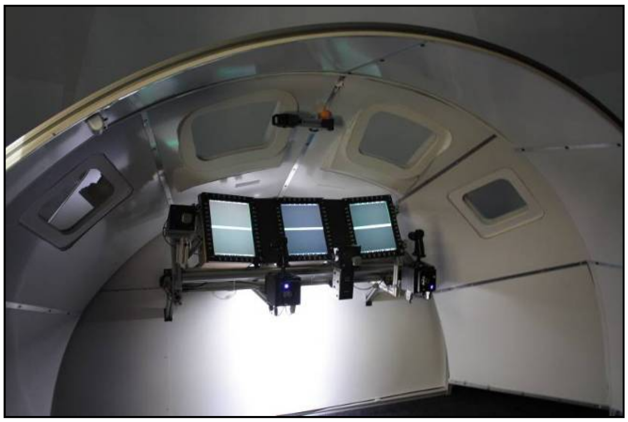

Figure 2 Orion Reconfigurable Operational Cockpit Simulation Facility

RPOD precision performance was assessed by the ability of the crew to successfully dock Orion to a target vehicle within the contact conditions limits required by the docking mechanism. These conditions are established by the NASA Docking Standard[2] (NDS) shown in Table 1. RPOD authority performance was assessed by the ability of the crew to acquire the docking axis by neutralizing the lateral motion expected along the anticipated approach trajectory. Iterations on these handling quality assessments were performed and, as the Program progressed; formal requirements verification would have been executed with the completed design.

Table 1

INITIAL CONTACT CONDITIONS "DESIGN TO" LIMITS [R.LIDS.0063]

Initial Conditions	**Limiting Value**
Closing (axial) rate	0.05 to 0.15 ft/s (0.015 to 0.045 m/s)
Lateral (radial) rate	0.15 ft/sec (0.045 m/s)
Angular rate	0.15 deg/sec about NDS X axis; vector sum of 0.15 deg/sec about NDS Y and Z axes
Lateral (radial) misalignment	4.2 ± .125 in. [106 ± 3 mm]
Angular misalignment	4.0 ± .25 degrees about NDS X axis; vector sum of 4.0 ± .25 degrees about NDS Y and Z axes

INCORPORATING AN INTERNATIONAL PARTNER

The Orion MPCV Program evolved from what was originally the Crew Exploration Vehicle under the NASA Constellation Program. While many of the technical goals for the spacecraft to provide reliable transportation for humans to and from space have remained essentially unchanged, the programmatic structure around Orion has greatly evolved. The most recent transformation was incorporating an international partnership with the European Space Agency (ESA) for development of a major subcomponent. ESA and their industry consortium have been given the responsibility to design and build a significant portion of the Orion Service Module. The Service Module components include the main propulsion system, solar arrays, and other mission critical hardware.

This division of responsibilities is significant as it relates to Guidance, Navigation, and Control (GNC) since the propulsion system effectors will now be developed and supplied by an external organization. The split of the GNC and propulsion systems between two partners necessitated a new approach to the specification of performance. Whereas prior requirement sets could specify integrated performance and Cooper-Harper ratings, these cannot be ascribed to a standalone propulsion system since their evaluation would not be possible without the corresponding GNC software and logic. Additionally, the ESA propulsion system development must be unconstrained in the choice of thrusters (with varying force generation) and configuration (quantity, location, and orientation). These design choices are at the discretion of the ESA and industry development teams and the specification of a performance capability is necessary to provide a basis for design and support independent verification. To address these programmatic constraints, unique propulsion system requirements would have to be developed specifying performance bounds capable of supporting manual piloting.

CONTROL REQUIREMENTS DEVELOPMENT

Given the need to enable independent verification of the propulsion system by ESA, the standard methodology to evaluate Cooper-Harper ratings for Orion is not sufficient. While Orion will ultimately still be responsible for verifying the manual piloting capability of the integrated system, a previously unnecessary decomposition of this requirement is needed to specify the performance of the ESA propulsion system. Further, the performance must account for the manual piloting considerations, such as the decoupling of rotational and translational motion, necessary to achieve the high Cooper-Harper rating.

The GNC team identified three areas needed to fully describe the performance space of the propulsion system. These are control authority, control impulse precision, and control residuals precision. Definitions of these terms as developed by the team are provided in Table 2 and were defined for each of the rotational (roll, pitch, yaw) and translational (x, y, z) axes. The actual performance values applied in these requirements were developed using the NDS contact conditions limits and the experience of the engineering team from prior development work. Control authority was established as a function of desired rotation and translation maneuver capabilities. Control impulse precision was calculated as a factor in the NDS docking conditions limits provided above such that the pilot would have the ability to command inputs sufficiently small enough to remain within the docking envelope. Lastly, control residual precision was also found by applying the NDS contact conditions limits such that an input in one axis would produce no more than particular fraction of the condition in the other axes.

Table 2

CONTROL REQUIREMENTS DEFINITIONS

Constraint	**Definition**	**Requirement Text**
Authority	The minimum accelerations that the propulsion system must be capable of producing; describes the gross force and torque capability of the system for pilot control	The Service Module shall produce accelerations greater than those shown in Table…
Impulse Precision	The maximum tolerable impulse values that the propulsion system must be capable of being producing; describes the ability of the pilot to provide small corrections to the flight	The Service Module shall generate minimum translation and rotation impulses that are less than the impulse values given in Table…
Residual Precision	The difference between the commanded and actual system response in all degrees of freedom; describes the purity of the system response to the pilot's input	For all translation and rotation impulses equal to or greater than the impulse values, the Service Module shall limit the translation and rotation residual to be less than the values in Table…

REQUIREMENTS EVALUATION

When the initial requirements for the ESA propulsion system were developed, it was necessary to validate them against the existing Orion design. This validation was accomplished through the application of both quantitative and qualitative means. The quantitative validation utilized a comparison of the existing NASA MPCV propulsion system to the proposed ESA design to evaluate system performance. During this analysis, it was found that two primary modifications were needed to arrive at the final set of requirement values. The first modification required a series of slight adjustments to the performance values to ensure the required ESA performance was equivalent to the baseline NASA design. As the NASA MPCV propulsion system and integrated guidance, navigation, and control system had already been found to comply with the tight Cooper-Harper level ratings, the analysis confirmed that the technique utilized to determine the values was appropriate. In conjunction with these slight performance adjustments, the wording of the requirements were exactingly phrased to ensure verification will occur as intended.

In particular, the requirement on residuals needed the most scrutiny and necessitated the most attention to phrasing given its unique development. The limits on mechanical operation of any thruster translates to a minimum impulse generation potential and specifies that thruster commands for values below this impulse value will be rounded to zero or "off". As a result, when thrusters are commanded in the vicinity of this minimum on-time the residuals are significant and must be left unconstrained. To eliminate this type of residual error, the responsibility resides in the GNC software system to account for this phenomenon in the thruster on-time calculation, as it is a known unavoidable result of the propulsion system limitations. Hence, the requirement wording needed to be precise so as to leave this portion of the requirement unconstrained and limit only those residuals at or above the minimum impulse size requirement.

An example of an early analysis of the residuals requirement is shown in Figure 3. In this analysis two proposed thruster configurations were examined for their residuals performance. The "keep out zone" for cross-coupling is defined by the vertical red line indicating the minimum impulse required in the given axis, and the horizontal red line indicating the maximum acceptable cross-coupling residual. It is clear from the results that one thruster configuration resulted in significant cross-coupling in the system response while still meeting the authority and impulse requirements. These results demonstrate the need to constrain the residuals to support manual piloting.

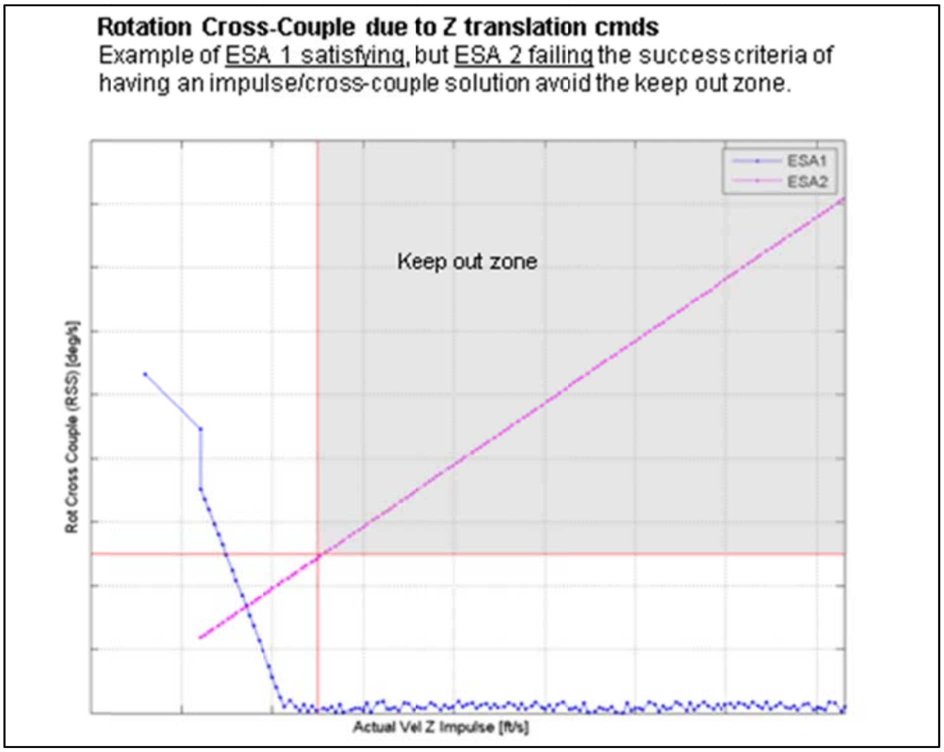

Figure 3 Analysis results for two proposed thruster configurations

The qualitative assessment of these requirements employed the existing Orion simulation capabilities to perform an engineering-level handling qualities assessment. In this technique, the Orion simulation, complete with the integrated GNC, crew displays and windows, and hand controllers, was updated with the thruster configuration and force-torque profile of the proposed ESA propulsion system that met the decomposed control requirements defined by NASA. This simulation was "flown" by two experienced astronauts who had participated in the prior NASA MPCV handling qualities assessment. The crew members judged that the system response of the ESA propulsion system was equivalent to the NASA MPCV design overall and presented no obvious issues. This further validated that, when all other factors were held the same, the decomposed control requirements for Service Module design functioned as intended and the ESA propulsion system would be capable of the performance necessary to support manual piloting required of the MPCV.

FORWARD PATH

Through the efforts of both the NASA and ESA teams and investigations such as this, the international partnership to develop the MPCV has been found to be technically viable. As a result, the agencies have formally agreed to proceed in collaboration on MPCV development. The immediate result of these requirements will be the finalization of the ESA propulsion system design to these specifications and their verification. Further, the integrated Orion system will also conduct verification of the higher level Cooper-Harper handling quality requirements prior to flight. As Orion proceeds through the design cycle and into verification, the control authority, impulse, and residual requirements will serve as the foundation of the GNC and propulsion system interface.

While developed to address the unique challenge of the NASA-ESA partnership on MPCV, these requirements are extensible to the development of other manually piloted spacecraft. The set of requirements developed describe the major features necessary to support manual piloting performance and provide a quantitative allocation to propulsion systems. Ultimately, this decomposition early in the design will reduce risk that the system will not be sufficient to meet qualitative Cooper-Harper ratings that can only be assessed once integrated system facilities are available.

CONCLUSION

To support the development and independent verification of a propulsion system by ESA for the MPCV Program, certain novel solutions were necessary to generate appropriate requirements. For the GNC and Propulsion systems, this primarily involved the specification of the control authority, control precision, and control residual capability to be met by the ESA design. These three requirements represent quantitative allocation of system performance derived from a qualitative Cooper-Harper handling quality rating requirement of level 1. This derivation of performance was based partly on the MPCV docking performance capabilities required to meet the NASA Docking Standard contact conditions limits and acquiring the docking axis on approach.

The requirement set described in this paper addresses the programmatic issue of developing a propulsion system independent of the GNC and wider vehicle systems. The requirements provide the flexibility to select thrusters and determine their placement and orientation on the European structure. These requirements were validated by comparison to the original Orion capability and through a manual piloting assessment of the simulated vehicle. The performance allocation to the propulsion system reduces development risk in meeting the Cooper-Harper manual piloting performance minimums. The development of these requirements has given the NASA and ESA GNC-Propulsion team valuable experience and has mitigated significant uncertainty in the ability to integrate systems developed by international partners.

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