Proximity Operation and Guidance Navigation and Control Design for HTV-X Automated Docking Demonstration Mission

HTV-X 自動ドッキング技術実証ミッションに係る近傍運用と航法誘導制御系設計 *

Takahiro SASAKI,[1] Yuki TOMITA,[2] Yoshinori KONDO,[2] Yuri HACHIYA,[2] Moeko HIDAKA,[1] Yuto TAKEI,[1] Ryo NAKAMURA,[1] and Toru YAMAMOTO[1]

佐々木 貴広,[1] 冨田 悠貴,[2] 近藤 義典,[2] 蜂谷 友理,[2] 日高 萌子,[1] 武井 悠人,[1] 中村 涼,[1] 山元 透 [1]

[1] *Research and Development Directorate, JAXA,* 宇宙航空研究開発機構 研究開発部門

[2] *Human Spaceflight Technology Directorate, JAXA,* 宇宙航空研究開発機構 有人宇宙技術部門

Japan Aerospace Exploration Agency (JAXA) is developing the next generation unmanned rendezvous visiting vehicle "HTV-X" to provide not only the advanced cargo transportation capability for the International Space Station but also the service as the technology tryout platform in low Earth orbit at the end of its mission. JAXA plans to demonstrate the proximity operation and automated docking technique with this plat foam. This paper presents the concept of a GNC strategy to address 6 degrees-of-freedom spacecraft attitude and position control for future HTV-X docking missions.

宇宙航空研究開発機構（JAXA）は，国際宇宙ステーション（ISS）への信頼性の高い貨物輸送能力を提供するだけでなく，ミッション終了後に地球低軌道上で技術実証を行うことを目的とした次世代型の無人ランデブ宇宙機「HTV-X」を開発している．JAXA はこのプラットフォームを用いて，近傍運用や自動ドッキング技術の実証を行う予定である．本論文では，将来の HTV-X のドッキングミッションにおける相対 6 自由度 (相対位置・姿勢) 制御における航法誘導制御 (GNC: Guidance, Navigation and Control) 系の概要を示す.

1. Introduction

The Japan Aerospace Exploration Agency (JAXA) is developing the next-generation unmanned rendezvous visiting vehicle “HTV-X”, which is the successor of the HTV (HIIB Transfer Vehicle:2009-2020) to provide not only advanced cargo transportation capability for the International Space Station (ISS) but also service as a technology tryout platform in low Earth orbit (LEO) at the end of its mission.[1] In the HTV-X2, JAXA plans to demonstrate proximity operation and an automated docking technique with this platform. The automated docking system is one of the critical technologies needed to realize sustainable activity on the future cis-lunar Gateway station where crew-based operations such as capturing the rendezvous vehicle by using real-time robotic arm operation on the ISS are currently not available (Fig. **1.**).

To successfully achieve the automated docking mission, the requirements for the physical contact condition (e.g., relative position, velocity, attitude, attitude rate) must be satisfied at initial contact with the docking mechanism. In this case, it is useful to confirm that a Monte Carlo (MC) analysis considering guidance, navigation and control (GNC) satisfies such docking requirements. Particularly in the final approach phase, the type and number of reflectors on the ISS tracked by rendezvous sensors such as LIDAR vary depending on the distance between the HTV-X and the ISS, and thus must be modeled rigorously and incorporated into the GNC simulation.

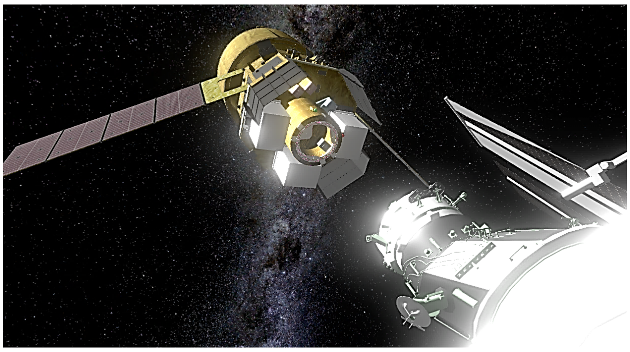

Fig. 1. **The automated docking conceptual sketch.**

This paper first presents an overview of a GNC strategy for demonstrating automated docking in future HTV-X missions and the concept of operation. It then focuses on LIDAR-based relative 6 degrees-of-freedom (DoF) navigation during the final approach phase, while switching reflectors tracked by LIDAR and navigation algorithms, depending on the distance.

2. Concept of Operation

The following factors must be considered for safe and successful automated docking with the ISS.

- Trajectory safety/Keep-out-sphere
- Field of View for LIDAR sensor
- PROX communication link stability (to avoid expected

NULL points)
- Navigation method switching from the RGPS to LIDAR
- Initial contact condition against the docking port

Table 1. **IDSS initial contact condition**

Initial Contact Condition	Limiting Value
Closing(axial) rate	0.05 to 0.10 m/s
Lateral(radial) rate	0.04 m/s
Pith/Yaw rate (vector sum of pitch/yaw rate)	0.20 deg/s
Role rate	0.20 deg/s
Lateral (radial) misalignment	0.10 m
Pitch/Yaw misalignment (vector sum of pitch/yaw)	4.0 deg
Roll Misalignment	4.0 deg

The trajectory safety for all maneuvers prior to entering the keep-out-sphere (KOS), which is defined as a 200-m radius zone around the ISS, shall target trajectories like the targeted maneuver and related free-drift trajectory that must stay outside the KOS for four orbits as required for the generic ISS operational safety condition. The vehicle's relative attitude shall be carefully considered in accordance with the vehicle's relative position against the ISS, so that the ISS is in the FOV of the LIDAR sensor and the antenna on both the HTV-X and the ISS during all approach and docking sequences, in order to confirm that abort or retreat is executable whenever the vehicle shows an abnormal status. The navigation method needs to be switching from the RGPS to the LIDAR sensor as the vehicle approaches close to the ISS. First, the RGPS must be used for a rough approach in the far phase from the ISS, but the accuracy of the RGPS cannot adequately support an approach to the ISS near the KOS, which means it is difficult to guarantee that the targeted maneuver and related free-drift trajectory stay outside the KOS only with the RGPS. Then LIDAR should acquire the target on the ISS for more accurate relative motion sensing near the KOS, whereas LIDAR is not valid when it is still far (several hundred meters) from the ISS. Therefore, a scenario where the navigation sensor handover from the RGPS to LIDAR occurs just before entering the KOS with the appropriate attitude is essential. At the final approach (20 meters to the docking port), there is a requirement from the active docking adapter installed on the vehicle that complies with the international system docking standard (IDSS),[2] where the vehicle's GNC must realize the ideal initial contact condition against the passive docking adapter on the ISS as described in Table 1 for successful docking.

As a result of considering these mission constraints, the one of the concepts of operation shown in Fig. 2 (circular flyaround method shown in the next section) is proposed. In the HTV-X2 mission, the docking demonstration will be started after departure from the ISS. There are two docking ports available in Node 2. In this paper, the IDA on the zenith side is selected for the feasibility study. The scenario shows that the HTV-X departs from the ISS out of the KOS in Steps 1 and 2, flies around the ISS through VPF to RPU in Step 3, and then makes a linear approach to the docking point in Steps 4 and 5. Now several scenarios have been investigated for the trade-off study[1,3] using a MC analysis and a linear covariance analysis (LCA).[4,5]

3. Final R-bar Approach

3.1. Overview of the Final Approach

From the R-bar 300-m hold point (RPU), the HTV-X initiates the final R-bar approach as shown in Fig. 3. In this final phase, the HTV-X needs to switch reflectors tracked by LIDAR and the navigation algorithm, depending on the distance between the HTV-X and the ISS. Figure 4 shows the control strategy only using LIDAR navigation. Range/line of sight (LoS) control is adopted from 300-meter hold point to the 20-meter hold point. In this case, only range and LoS angle are observed by LIDAR, so only relative position is obtained and the desired relative attitude is determined based on the LVLH attitude calculated by GPSR and/or orbit propagation. Relative 6-DoF control is adopted from 20-meter hold point to the initial contact point.

3.2. 300-meter Hold Point to 20-meter Hold Point

At the 300-meter hold point, LIDAR starts facing the target markers on the IDA and can obtain its range and azimuth/elevation data from the IDA, whereas relative attitude measurement is not yet available. During the approach to the 20-meter hold point, the star tracker and gyro sensor are still utilized for attitude estimation, and the HTV-X's attitude is controlled in the LVLH frame. LIDAR will obtain both the relative position and attitude value before arrival at the 20-meter hold point when the vehicle approaches close enough to the IDA so that the four target markers on PDT are separately detectable by the LIDAR sensor for 6-DoF navigation. The control and navigation logic will be similar to that used in the phase of ISS flyaround in cases 2 and 3 (the shortcut method).

3.3. 20-meter Hold Point to Initial Contact Point

This is the final approach phase in the docking demonstration mission. In this phase, relative translational (position and velocity) control and relative rotational (attitude and attitude rate) control are performed. All thrusters are deactivated and the free-drift sequence will be transferred when the distance between the active(HTV-X) and passive(IDA) docking mechanisms becomes less than 1 meter. This subsection ensures that relative variables from numerical simulation satisfy the required initial contact limiting values in Table 1. In this study, the approach (closing) velocity is tracked at 7.5 centimeters per sec. Figure 5 shows the relative velocity guidance.

Since effects of multipath interference with the ISS must be considered in operations in the vicinity of the ISS, the star tracker and GPSR measurements are not included in the navigation filter for estimating the relative position, velocity, attitude, and attitude rate between the HTV-X and the docking target in this phase. Therefore, this study considers that 3D LIDAR-based navigation is adopted in the final approach phase, which leads to an easy design of FDIR and the navigation filter.

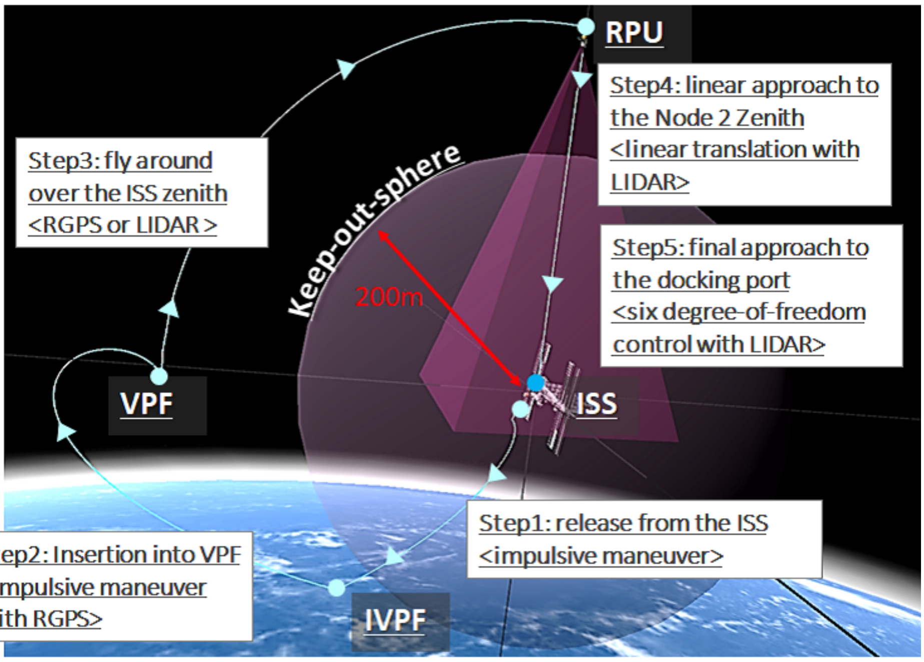

Fig. 2. **Concept of Approach Operation.**

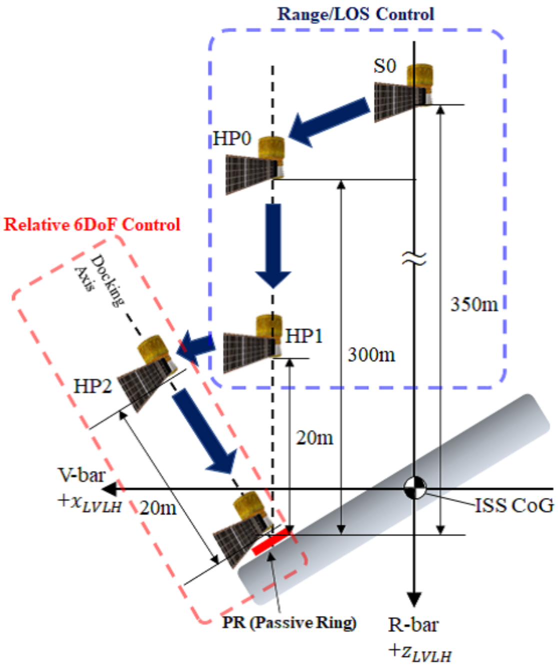

Fig. 3. **Overview of the final approach.**

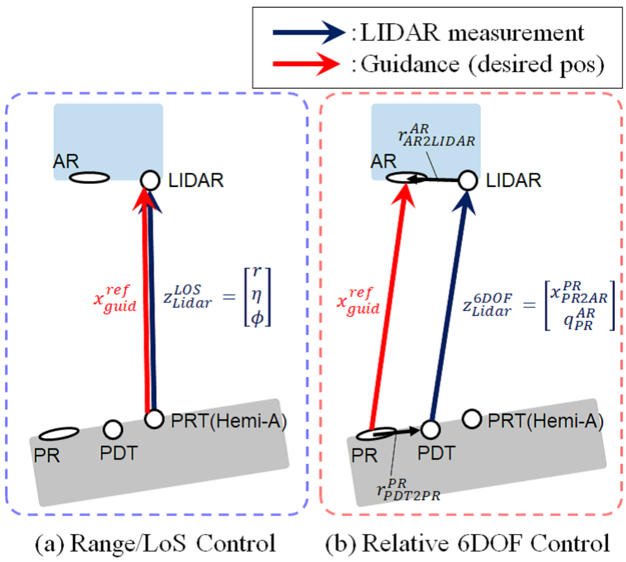

Fig. 4. **Control strategy using only LIDAR.**

4. Monte Carlo Simulation Results

MC simulations are conducted to confirm the feasibility of the HTV-X docking mission. Figure 6 shows 300-run MC simulation results that present the time histories of relative position, velocity, attitude angle (3-2-1 Euler angle representation), and attitude rate. The red lines represent the limiting initial contact requirement in Table 1. From the simulation results, it was verified that all relative state variables met the IDSS requirements at the initial contact point.

5. Conclusions

The HTV-X, which is the successor of the HTV cargo vehicle, has technology demonstration capability, and JAXA plans to tryout the automated docking system in the HTV-X2 with ISS Node 2. JAXA conducted a feasibility study of the GNC strategy by assuming docking with the Node 2 zenith, and showed that the HTV-X design is capable of conducting docking operation by implementing the appropriate approach planning and control methodology. Future work will include the confirmation of all scenarios through the mission life cycle through numerical simulations, and FDIR design by using a GNC simulator. Then, the minimum ΔV leaving undock

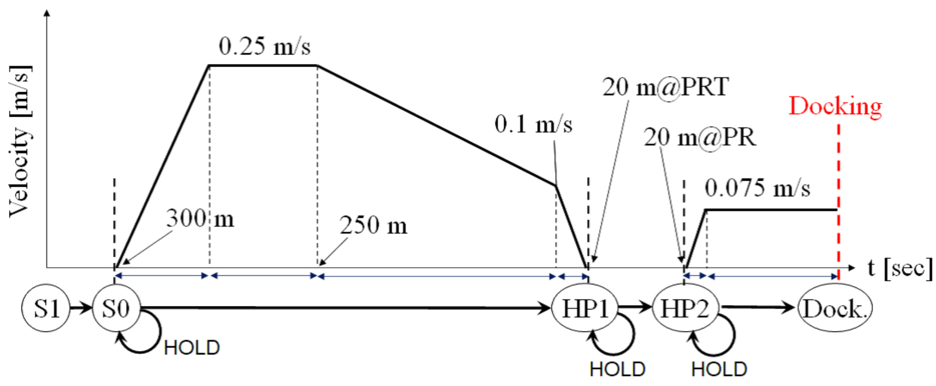

Fig. 5. **Relative velocity guidance.**

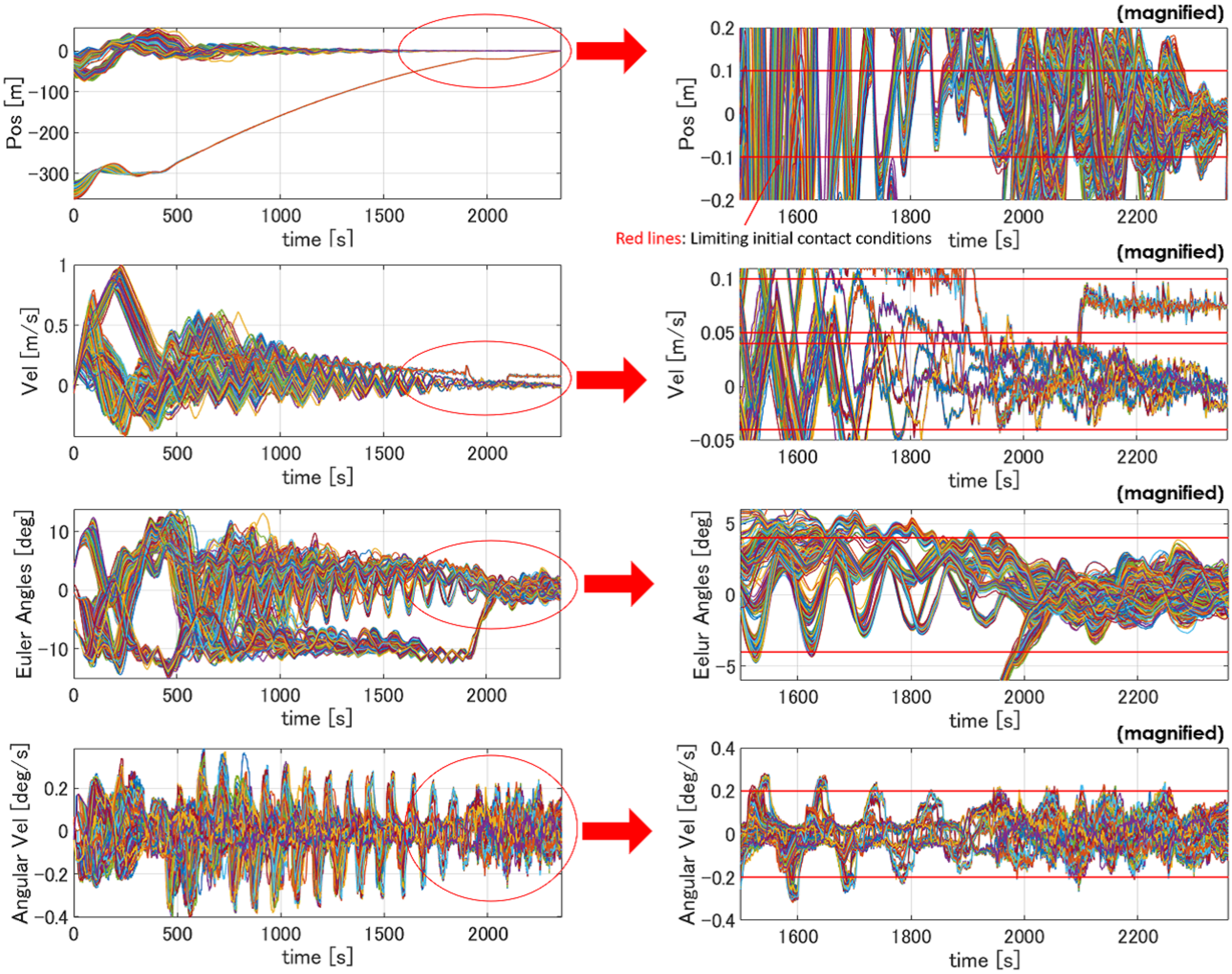

Fig. 6. **Relative state variables (300 run MC).**

conditions and the required time to start thruster control will be clarified through MC analysis.

Acknowledgment

The authors wish to thank all the advisors on the HTV-X Project Team and the JAXA Research and Development Directorate for supporting the concept research on GNC for the automated docking demonstration mission.

References

1) Y. Tomita, et al. "Development of Guidance, Navigation, and Control Strategy for the Automated Docking Operation on HTV-X," 71st International Astronautical Congress (IAC), The CyberSpace Edition, 12-14 October 2020.
2) International Docking System Standard (IDSS) Interface Definition Document (IDD) Revision E.
3) M. Hidaka, et al, "ISS Fly Around Strategy for Automated Docking on HTV-X," 31st Workshop on JAXA Astrodynamics and Flight Mechanics , 2021.
4) D. K. Geller, "Linear Covariance Techniques for Orbital Rendezvous Analysis and Autonomous Onboard Mission Planning," *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 6, 2006, pp. 1404–1414.

5) D. K. Geller, M. B. Rose and D. C. Woffinden, “Event Triggers in Linear Covariance Analysis with Applications to Orbital Rendezvous,” *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 1, pp. 102-111, 2009.