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Result of Autonomous Rendezvous Docking Experiment of Engineering Test Satellite-VII

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On 7 July 1998, Engineering Test Satellite-VII (ETS-VII) successfully performed the first autonomous rendezvous docking (RVD) between uninhabited spacecraft ever. RVD technology is essential for future space activities, such as logistic support for the International Space Station. The National Space Development Agency of Japan developed ETS-VII to demonstrate autonomous RVD technologies. ETS-VII carried two RVD experiment flights successfully in 1998. We introduce the autonomous RVD system of ETS-VII and show the results and evaluations of two RVD experiment flights. We realized autonomous uninhabited RVD, and its performance was better than required.

Introduction

On 7 July 1998, Engineering Test Satellite-VII (ETS-VII) successfully performed the first autonomous rendezvous docking (RVD) between uninhabited spacecraft ever. Figure 1 shows ETS-VII during the RVD experiment. The RVD technology to meet and to connect two spacecraft in orbit is an essential technology for future space activities, such as logistic support for the International Space Station (ISS). In the early 21st century, humankind will expand its scope of activities to outer space. The ISS, as well as various other spacecraft and vehicles will be in low Earth orbit (LEO). The National Space Development Agency of Japan (NASDA) participates in the ISS project and is now developing the H-II Transfer Vehicle (HTV) for ISS logistics support. Figure 2 shows the HTV. To realize these plans for space vehicles, some advanced technologies must be developed. In particular, the RVD technology is prerequisite for the ISS logistic support by the HTV, for in-orbit servicing of the structure, for in-orbit assembly of the huge space structure, and for sample return from the moon or planets.

HTV will be the first uninhabited vehicle that performs RVD to the crewed ISS. To perform in-orbit demonstration of the autonomous RVD technology before the practical RVD mission, we developed ETS-VII. ETS-VII consists of two satellites, the chaser named Hikoboshi, and the target named Orihime (Fig. 1). They weigh 2.5 and 0.4 ton, respectively. During the RVD experiment, the chaser releases the target and moves away from it. Then the chaser approaches and docks with the target. The satellites were launched together by NASDA's H-II rocket on 28 November 1997 and injected into their mission orbit, which is 550 km in height and 35 deg in inclination.

The first autonomous RVD experiment flight (FP-1) was carried out successfully on 7 July, the day of Tanabata, Japanese Stellar Festival. The first experiment day was chosen because the chaser and the target satellites had been named after the hero and the heroine of Tanabata. In this flight, autonomous docking from 2 m (start point of docking phase) was demonstrated. Then, the second RVD experiment flight (FP-2) was started on 7 August 1998. In this flight, attitude anomalies occurred, and the chaser's flight was to 12 km in range. As a result, the chaser successfully mated with the target on 27 August using global positioning system (GPS) relative navigation as well as rendezvous laser radar (RVR) navigation. Through these two flights, the autonomous RVD technologies in the relative approach phase (from 10 km to 500 m), in the final approach phase (from 500 to 2 m), and in the docking phase (within 2 m) were verified on orbit.

The experimental results showed that the guidance, navigation, and control (GN&C) function and flight management function worked properly and that the performance of the RVD components and the GN&C were better than their requirements. We present the autonomous RVD system of ETS-VII and report the results and evaluations of these two RVD experiment flights.

RVD System Concept

NASDA is now developing HTV, which will be the first uninhabited space vehicle to perform rendezvous to the crewed ISS for logistic support. Therefore, the main objective of the ETS-VII RVD experiment is to verify and establish autonomous RVD by an uninhabited spacecraft. The ETS-VII RVD system has three major characteristics: 1) autonomous RVD by uninhabited vehicles, 2) safe RVD, and 3) low-impact docking.

Uninhabited RVD is categorized into two kinds, an autonomous RVD and a remotely piloted RVD. We selected an autonomous RVD system as the primary system in consideration of the following three points:

1) It will be applied for various spacecraft.

2) It can be highly accurate and highly reliable because it doesnot depend on human ability.

3) It doesnot need a continuous communication link between the RVD vehicle and ground stations.

Moreover, we added the function of remotely piloted RVD to pursue another application.

If an uninhabited space vehicle tries to perform RVD with the crewed ISS, a very high degree of safety is required. We paid special attention to safety design, and adopted two fail safe criteria in a proximity area.

Although the closing velocity is from 5 to 10 cm/s in conventional American and Russian docking (impact docking), we selected low-impact docking with 1-cm/s closing velocity. High control accuracy is needed for low-impact docking. On the other hand, conventional impact docking needs a heavy docking mechanism for energy damping. Moreover, low-impact docking is more reliable and safer than conventional impact docking because it is easy to avoid collision and to retry docking if any contingencies occur. As a result, we decided to establish low-impact docking technology.

Objective of RVD Experiment

The sequence of ground-up RVD is divided into the following five phases: 1) launch, 2) orbit transfer, 3) relative approach, 4) final approach, and 5) docking/berthing.

The main objective of the ETS-VII RVD experiment is to demonstrate and to verify the autonomous RVD technologies for three phases, the relative approach, the final approach, and the docking. The main technologies for the orbit transfer phase, such as the GPS

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absolute navigation and an autonomous orbit transfer, will also be verified through the experiment. The ETS-VII RVD experiment will demonstrate remotely piloted RVD as well as autonomous RVD.[1]

The main technical items to be verified are as follows:

1) For RVD instrument technology, the function and performance of the rendezvous navigation sensors such as the RVR and the docking mechanism (DM), which are newly developed for the ETS-VII RVD, will be verified.

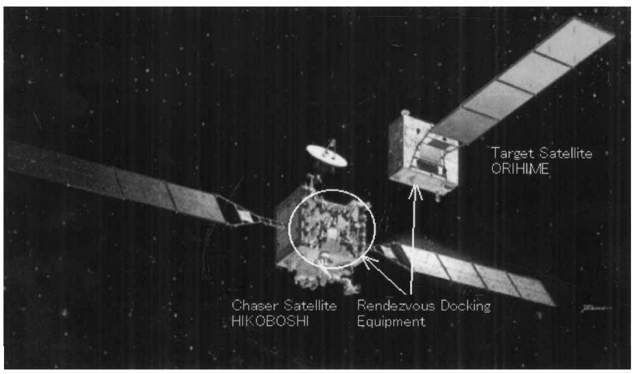


Fig. 1 ETS-VII satellites on orbit (during RVD experiment).

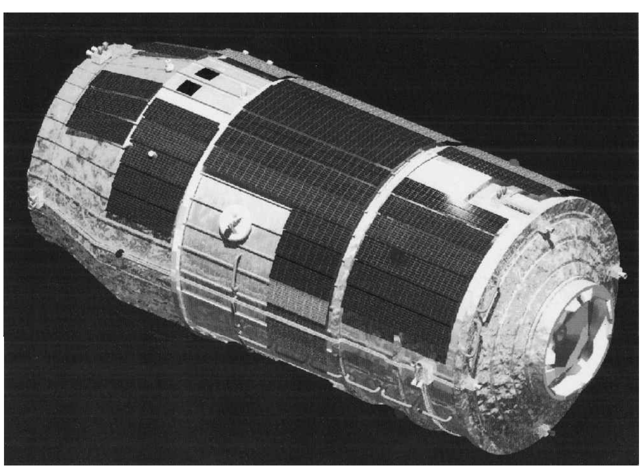


Fig. 2 Artist's image of HTV.

2) For RVD GN&C technology, RVD navigation and guidance logic, which issues maneuver commands to approach along an appropriate trajectory and an onboard autonomous flight management function, which includes mode control, will be verified.

3) The RVD operation technologies to control two space vehicles during the RVD flight, especially safety insurance operations using onboard flight management functions will be demonstrated. Additionally, operation technology using a data relay satellite, and teleoperation technology will be mastered.

ETS-VII RVD Experiment System

The ETS-VII RVD experiments are performed using both satellites' bus system (attitude and orbit control system, thrusters, etc.), the RVD subsystem on both satellites, a ground support system, and communication links. The communication link between ETS-VII and the ground control system located at NASDA's Tsukuba Space Center, is realized using NASA's tracking and data relay satellite (TDRS). Figure 3 shows the RVD experiment relating system. The chaser has the Guidance control computer (GCC), the GPS receivers (GPSR), the RVR, a camera-type proximity sensor (PXS), the accelerometer, and the DM, and the chaser performs RVD control actively. The target is also equipped with the GPSR, passive RVR reflectors, a PXS marker, and DM handles, and the traget performs only attitude control. Two charge-coupleddevice (CCD) cameras, a viewing camera (VC) and a docking camera (DC) on the chaser are also used during the RVD experiment. The VC is used to monitor the approach, and the DC is to monitor the movement of the DM and the target during docking.

ETS-VII performs autonomous RVD so that a navigation function to measure and estimate the relative position and velocity between the chaser and the target is needed. ETS-VII has three navigation methods. One of these is selected automatically depending on the distance between the two satellites: the GPS relative navigation is used in the relative approach phase (from 10 km to 500 m), the RVR navigation is used in the final approach phase (from 500 to 2 m), and the PXS navigation is used in the docking phase (within 2 m). The system design is described in detail in Ref. 2.

RVD Experiment Results

RVD Experiment FP-1

RVD flight FP-1 was successfully completed on 7 July 1998. Main flight of FP-1, from separation to docking, is executed during one event of the TDRS (one event is about 40 min). The FP-1 was carried out as follows.

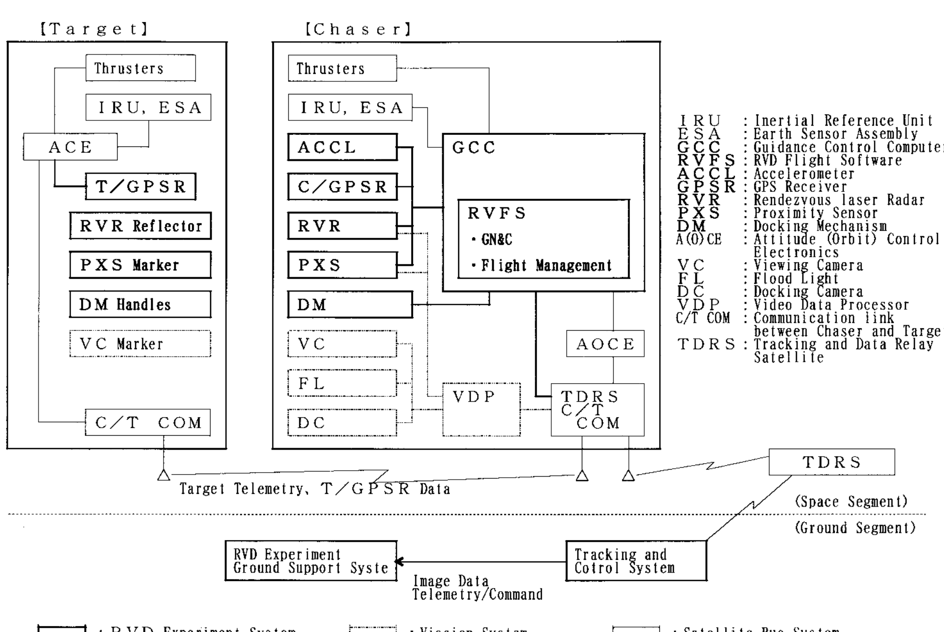


Fig. 3 ETS-VII RVD experiment relating system.

Table 1 Verified items through FP-1 and FP-2

Property	Checkout	FP-1	FP-2	Third experiment flight
Instrument				
DM	X	X	X	
PXS	X	X	X	
RVR	X		X	
GPSR	X		X	
GN&C				
Separation	X	X	X	
Docking	X	X	X	
PXS relative navigation	X	X	X	
6DOF control		X	X	
RVR relative navigation	X		X	
Reference trajectory guidance			X	
LOS control			X	
GPS relative navigation	X		X	
C–W guidance			X	
VIC control			X	
R-bar approach flight				X
Operation				
Flight management	X		X	X (Mode/sequence control related to remote pilot and CAM)
Contingency			X(DA)	X (CAM)
Remote pilot rendezvous				X (Remote pilot)

First, the ground support crews sent separation command from Tsukuba Space Center to the chaser, and the chaser pushed out the target and left at the low speed of 1.8 cm/s. The chaser started to control relative position and attitude automatically and separated up to VP (vicinity point: 2-m hold point). The two satellites continued formation flight for 15 min keeping a constant distance of 2 m with a few centimeter range accuracy using PXS navigation and relative six-degree-of-freedom (six-DOF) control. Then, the ground crews sent the approach command to the chaser, and the chaser started to approach the target at the low speed of 1 cm/s and captured the handles of the target by the DM before contact. At last, the chaser docked with the target completely. Figure 4 is a series of images in docking phase taken by the DC on the chaser.

RVD Experiment FP-2

RVD flight FP-2 was started on 7 August. It would take about 4 h after separation to complete docking in the original plan, but we needed 3-weeks flight to complete docking because of several thruster misfires.

The chaser separated the target, and performed V-bar departure flight up to the 525-m hold point as planned. However, during V-bar approach, the attitude deviation occurred and, thus, the chaser executed disable abort (DA) automatically by its onboard safety management function and flew up to the retreat point (2.5 km forward of the target). Final approach to the target was attempted twice, from 8 August to 13 August; however, the attitude deviations occurred and the chaser moved to safety mode again.

After investigation, it was learned that the attitude deviations were caused by misfiring thrusters. Thruster firing signals were issued by the valve drive electronics, but the imported valves did not open, and thrusters could not fire correctly. The chaser has two sets of 14 thrusters to control its orbit and attitude. The thrusters can not generate forces independently of the generating torques. Only three thrusters are assigned to generate force on the Z axis and to generate torques around the roll and pitch axes. Therefore, if a thruster does not fire properly, then attitude deviation will be caused because three DOF cannot be controlled by two thrusters. It seemed that the thruster misfiring happened mainly during the final approach, when many thruster firing at intervals of from 1 to 3 s are needed. Considering that point, we modified the rendezvous flight software (RVFS) and the approach method to minimize thruster firing in the Z direction and then retried final approach 26 August. As the result of these modifications of the RVFS and approach method, we accomplished autonomous rendezvous docking on 27 August.

Evaluation of Flight Result

In the original experiment plan, RVD instruments, GN&C functions, and operation technologies needed for the uninhabited RVD would have been verified through six experiment flights. However, actually the maximum range in which the chaser flew in FP-2 was about 12 km, and the chaser approached from that point and docked with the target successfully. As a result, several items to be verified after FP-2, such as DA and recovery operations using the GPS relative navigation, were already verified. Table 1 summarizes technical items verified through FP-1 and FP-2 and items verified in the third experiment flight. It can be seen that main items had been almost verified through FP-2 and that all remaining items were verified in the third experiment flight. The evaluation of the GN&C performance in each phase through FP-1 and FP-2 will be discussed in detail in the following.

Table 2 Separation accuracy of docking mechanism (measured by PXS)

Parameter	FP-1	FP-2	Requirement
Velocity			
V_x, mm/s	17.71	17.52	18 ± 4.1
V_y, mm/s	−0.4	−0.4	±1.0
V_z, mm/s	0.1	0.4	±1.0
Angular rate			
Roll, deg/s	−0.014	−0.013	±0.07
Pitch, deg/s	0.026	−0.044	±0.09
Yaw, deg/s	0.043	0.051	±0.09

Separation

Accurate separation by the DM is very important because the PXS should keep the target marker in view for measurement after separation. Table 2 shows the separation accuracy in comparison with its requirement. It could confirm that in-orbit performance was better than the requirement.

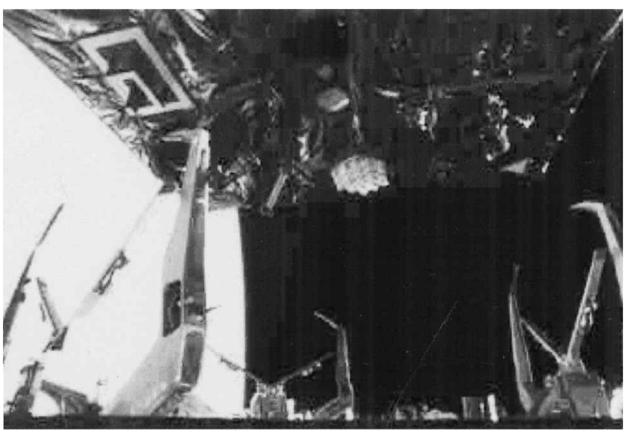
Low-Impact Docking

ETS-VII performed low-impact docking. The chaser approached at low speed, 1 cm/s, and the chaser's DM latches captured the target's handles as designed. Position accuracy at capture was about 1 cm (Fig. 4). Figure 5 shows accelerations of the chaser during docking measured by the accelerometer. The peak acceleration was less than 9 mm/s^2. We could verify that it accomplished low-impact docking.

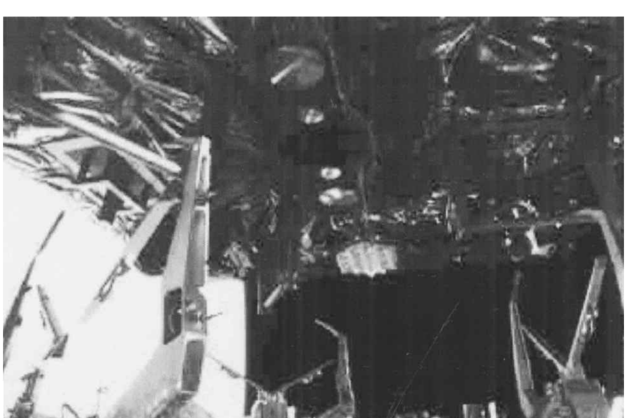
Relative Six-DOF Control and PXS Navigation

In the docking approach phase, relative six-DOF control using the PXS navigation is executed. Finally, the chaser captures the target's handles by the DM. Figure 6 shows the result. These graphs show relative position and attitude measured by the PXS after

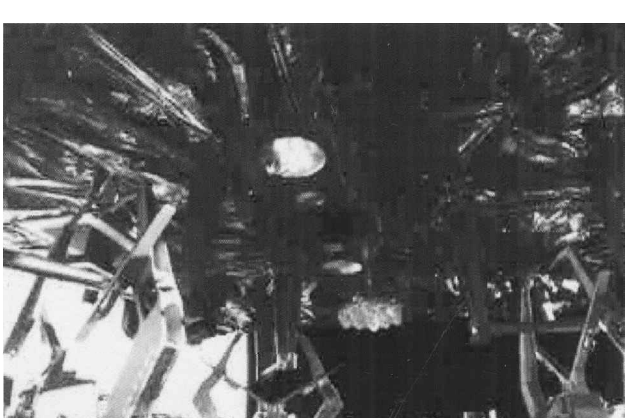
Approaching about 1.5 m



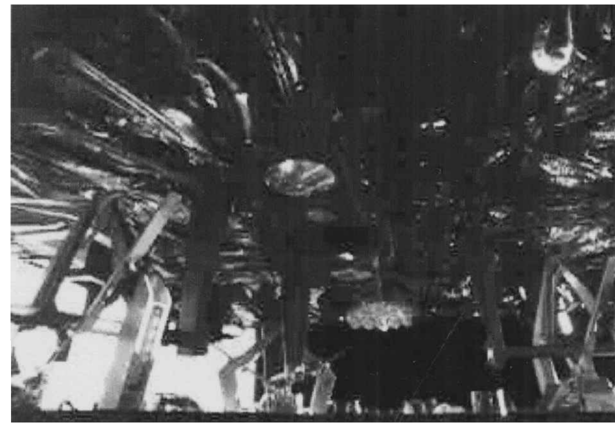
Approaching about 1.2 m



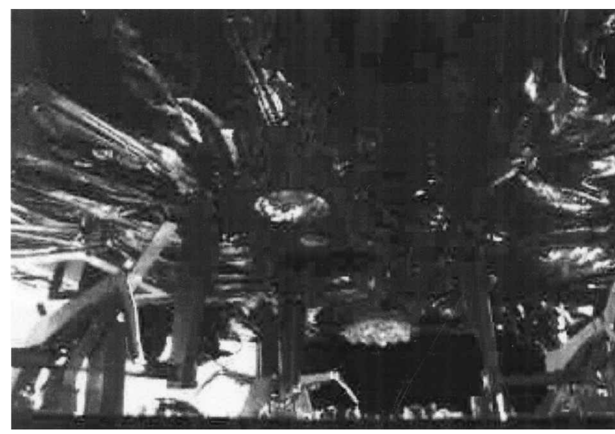
Passing over outer marker (0.75 m)



Capturing before contact (0.58 m)



Contact



Drawing into combining position

Preloading

Docking completed

Fig. 4 Photographs in docking phase taken by the DC: upper vehicle is the target, lower vehicle is the chaser, and the bright sphere is Earth.

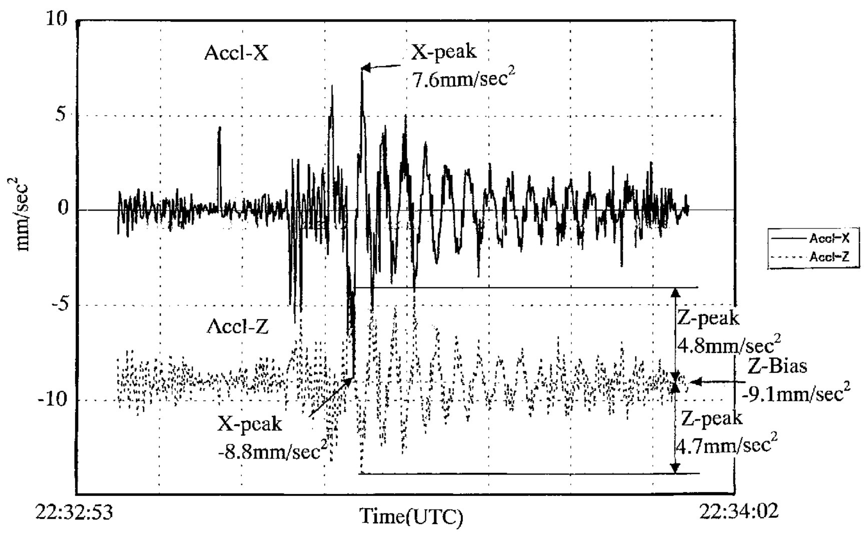


Fig. 5 Acceleration during low-impact docking.

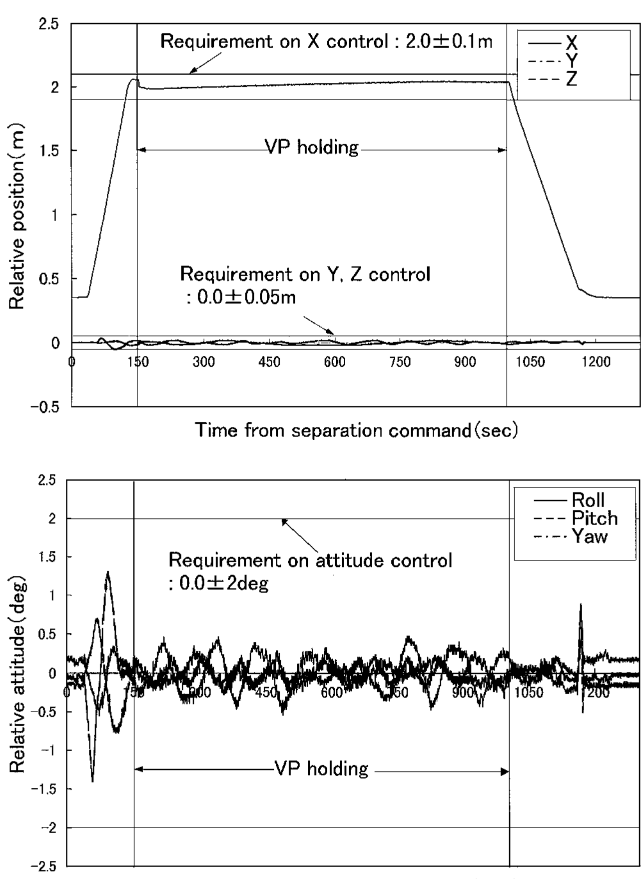


Fig. 6 Results of six-DOF control in FP-1; relative position and attitude measured by PXS.

separation, comparing with the requirements during holding at VP point.

The requirement on position control accuracy is within 10 cm, and actual control errors were about 2 cm. The requirement on attitude control accuracy is within 2 deg, and control errors were within 0.5 deg in each axis.

The PXS is a navigation sensor using image processing technology and calculates the relative position and attitude of the chaser related to the target from the positions of reflected marker images taken by the CCD. We evaluated the accuracy of the PXS in orbit by comparison with the measurement data of final ground test after the target had been mated with the chaser. The measurement data are summarized in Table 3. The measurement values in orbit and of the ground test agreed within 1 mm. Random errors were within 0.2 mm in relative position and less than 0.1 deg in relative attitude, respectively. They were better than requirements, which were 20 mm in range (X direction) and 0.8 deg in attitude, respectively. As a result, we could verify that the GN&C performance in the docking approach phase were much better than requirements.

Table 3 Measurement accuracy of the PXS

Parameter	Ground	Average in orbit	Difference	Random (3σ) in orbit
		Relative position		
X, m	0.4315	0.4321	0.0006	0.0002
Y, m	−0.0004	0.0002	0.0006	0.0001
Z, m	0.0001	0.0000	0.0001	0.0000
		Relative attitude		
Roll, deg	0.272	0.275	0.003	0.018
Pitch, deg	0.167	−0.003	0.170	0.017
Yaw, deg	0.052	−0.099	0.151	0.059

Table 4 Measurement accuracy of the RVR

Parameter	Ground	Average in orbit	Difference	Random (3σ) in orbit
Range, m	0.4957	0.4782	0.0175	0.0053
LOS angle				
Az, deg	0.0238	0.0362	0.0124	0.0070
El, deg	−0.0052	−0.1346	0.1294	0.0041

Reference Trajectory Guidance and RVR Navigation

In the final approach phase, the chaser approaches along V-bar by an explicit guidance law of reference trajectory based on RVR navigation. Figure 7 shows the position/velocity commands and that of RVR navigation. The difference between the position/velocity commands and that of RVR navigation was negligibly small. It could be confirmed that performance of reference trajectory guidance was as good as that of the RVR navigation.

The RVR is a three-dimensional position sensor using laser radar. We adopted a static head with a two-dimensional CCD instead of a mechanical scanning head. Range is measured by comparing the phases of return beam and transmitted beam. Line-of-sight (LOS) angles are measured from the corner-cube reflector images taken by the CCD.

We evaluated the accuracy of RVR in orbit by comparison with the measurement data of the final ground test after the target had been mated with the chaser. The measurement data are summarized in Table 4. The measurement value in orbit and of the ground test agreed within 2 cm in range. It was better than required (10 cm). The differences of LOS angle measurements between those in orbit and on ground were about 0.1 deg. It also met the requirement after

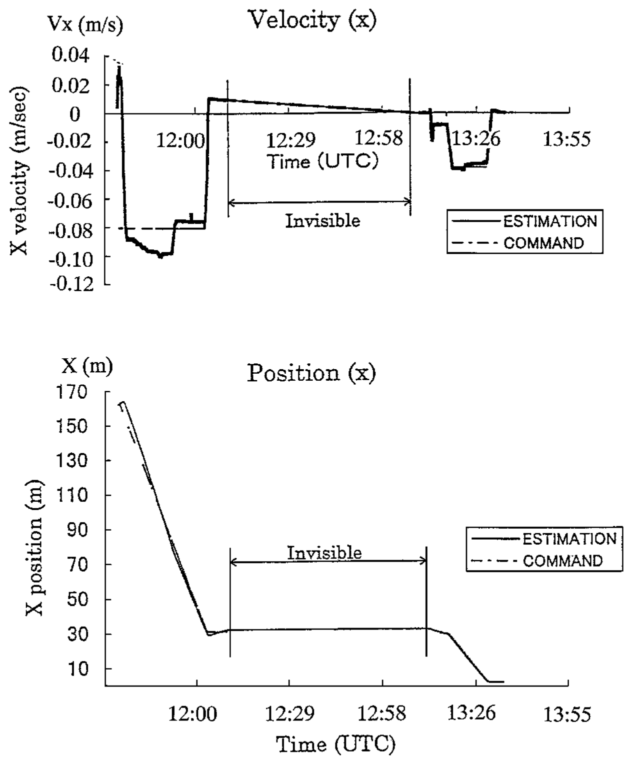


Fig. 7 Position/velocity during V-bar approach by reference trajectory guidance.

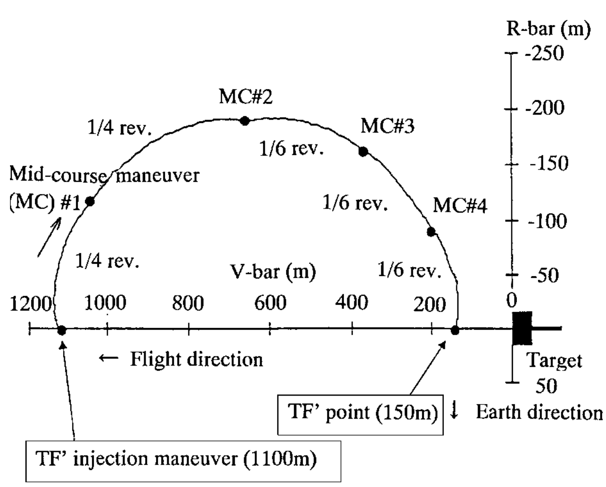


Fig. 8 Trajectory of 150-m injection by C–W guidance.

calibration. Random errors were also less than requirements. As the result, we could verify that the GN&C performances in the final approach phase were much better than requirements.

Clohessy–Wiltshire Guidance and GPS Relative Navigation

In the relative approach phase, the chaser approaches by the Clohessy–Wiltshire (C–W) guidance law, which uses the C–W solution of Hill's equation. Orbit maneuver command (required ΔV) is calculated by the guidance law, and velocity increment cutoff (VIC) is performed using accelerometer measurement. Figure 8 shows the trajectory of injection from the 1100-m point to 150-m point using C–W guidance. That was estimated by the GPS relative navigation. We know that actual injection accuracy was about 20 m, after evaluation, although the requirement on that is within 80 m.

The GPS relative navigation estimates relative position and velocity in Hill's coordinate system. The chaser GPSR (C/GPSR) performs the GPS relative navigation. Both satellites have GPSRs, and the C/GPSR processes the difference of both satellites' pseudo-range and delta-range data as measurement data and estimates their relative position and velocity using an extended Kalman filter.[3] We evaluated the accuracy of the GPS relative navigation in orbit by comparison with raw measurement data of the RVR as the reference. Figure 9 shows ranges estimated by the GPS relative navigation and that of RVR measurement. Both GPS and RVR range data corresponded well, and the difference between them was a few meters. The accuracy of the GPS relative navigation is also evaluated during the mating flight.

The distance between the antennas of the C/GPSR and the target (T) T/GPSR was previously known. Table 5 shows the accuracy of the navigation, led by the distance of antennas. It can be seen that the accuracy in position estimation was within 10 m, although the requirement on that is 26 m. As a result, we could verify that the GN&C performances in the relative approach phase were much better than requirements.

Table 5 Accuracy of GPS relative navigation

Parameter	Average	Random (3σ)
	Relative position	
X, m	0.155	2.406
Y, m	−0.558	2.844
Z, m	2.711	4.026
	Relative velocity	
Vx, m/s	−0.0028	0.0060
Vy, m/s	−0.0014	0.0039
Vz, m/s	−0.0036	0.0063

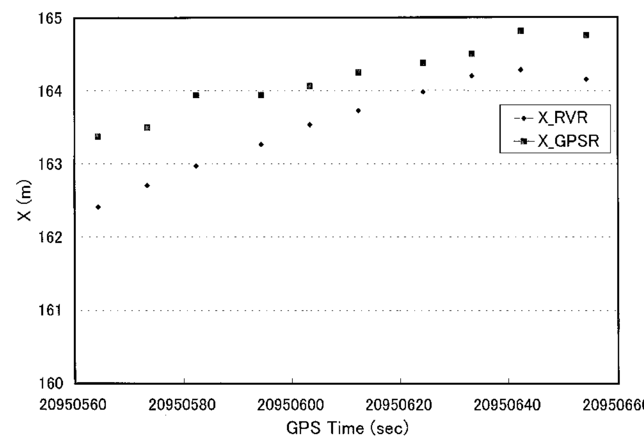


Fig. 9 Ranges by the GPS relative navigation and the RVR.

Autonomous Flight Management

We studied on an autonomous RVD system. In addition to GN&C functions, our RVD system has the flight management function, which consists of mode/sequence control, component redundancy management, and safety management. Safety management is especially important because the ETS-VII RVD technology will be applied for the HTV, which perform RVD with the crewed ISS. Flight management is operated by the RVFS installed in the GCC. The RVFS monitors and checks satellite's attitude, communication link, components' self-check status etc. If a malfunction of a component is detected, the RVFS will change the component to a redundant one. Moreover, if a consecutive malfunction of a redundant component should be detected, the RVFS will execute automatically the collision avoidance maneuver (CAM), within 30 m from the target or a DA out of 30 m.

In FP-1 and FP-2, mode/sequence control by the RVFS worked well. For example, the RVFS judged the RVR acquisition and changed its flight mode from the relative approach mode to the V-bar approach mode. In FP-2, when the attitude anomaly occurred during the V-bar approach, the RVFS detected it and the unlock of both RVRs. Thus the RVFS changed its flight mode to the safety mode, and it executed DA automatically. This prevented the satellites from collision and ensured safe flight. During the two experiment flights, we could verify that autonomous flight management worked as designed. This included mode/sequence control and safety management.

Conclusions

In this paper, the autonomous RVD system of the ETS-VII and the results and evaluations of two RVD flights are discussed. It is shown that the ETS-VII RVD system worked as designed and that the performances of the RVD components and GN&C exceeded their requirements.

The ETS-VII RVD system is the first autonomous RVD system ever and has a practical use in view. We believe that the technologies developed through the ETS-VII project will be applied to advanced space vehicles such as the HTV, the OSV, and lunar or Mars explorers.

References

[1] Kawano, I., Mokuno, M., Horiguchi, H., and Kibe, K., "In-Orbit Demonstration of an Unmanned Automatic Rendezvous and Docking System by the Japanese Engineering Test Satellite ETS-VII," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, AIAA, Washington, DC, 1994, pp. 950–960.

[2] Kawano, I., and Mokuno, M., "Automated Rendezvous Docking System of Engineering Test Satellite VII," *Advances in the Astronautical Sciences,* Vol. 96, July 1997, pp. 751–765.

[3] Kawano, I., Mokuno, M., and Kasai, T., "Relative GPS Navigation for an Automated Rendezvous Docking Test Satellite ETS- VII," *Proceedings of the 10th International Technical Meeting of the Satellite Division of the Institute of Navigation* (ION GPS-97), Inst. of Navigation, Kansas City, MO, 1997, pp. 707–715.

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