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# Attitude Control Experiments of a Robot Satellite

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**The Engineering Test Satellite VII of the National Space Development Agency of Japan, launched in 1997, has a 2-m-long robot arm to conduct space robot technology experiments. The robot arm was teleoperated from the onground control station using a communication link through a data relay satellite in geostationary orbit. To maintain satellite attitude stability and the direction of the intersatellite communication antenna vs the robot arm's motion, coordinated satellite attitude control and coordinated robot-arm control were introduced. Coordinated satellite attitude control was realized by adding feedforward angular momentum cancellation in addition to traditional feedback attitude control. The coordinated robot-arm control was to manage the robot arm's angular momentum within the capability of the satellite attitude control system. Gain scheduling control was also tested to reduce the satellite attitude error that was caused by the robot arm motion and showed good performance. With these controls, the onboard robot arm conducted various tasks safely and successfully. Robot-arm motions while the satellite attitude was not actively controlled were also tried. However, it is shown that the robot-arm motion on a free-motion satellite was not easy due to the gravity-gradient torque and other disturbance torques.**

## Nomenclature

$\boldsymbol{E}$ = unit vector along the satellite body axis
$\boldsymbol{H}_{\mathrm{RBT}}$ = angular momentum vector of robot arm
$\boldsymbol{H}_{\mathrm{RW}}$ = angular momentum vector of reaction wheels
$\boldsymbol{H}_{\mathrm{sat}}$ = angular momentum vector of satellite platform
$\boldsymbol{H}_{\mathrm{sys}}$ = angular momentum vector of satellite system
$I_{\mathrm{sat}}$ = inertial tensor of satellite system
$I_x$ = moment of inertia of the satellite around $X$ axis
$I_y$ = moment of inertia of the satellite around $Y$ axis
$I_z$ = moment of inertia of the satellite around $Z$ axis
$R$ = orbital radius
$\boldsymbol{R}'$ = orbital position vector of the satellite
$\boldsymbol{T}_d$ = disturbance torque vector
$\boldsymbol{T}_g$ = gravity-gradient torque vector
$\theta$ = satellite's pitch attitude
$\mu$ = Earth's gravity constant
$\phi$ = satellite's roll attitude
$\omega_{\max} \in R^3$ = allowable maximum satellite angular rate
$\omega_{\max\text{-est-1}} \in R^3$ = estimated maximum satellite's attitude rate after start of robot-arm motion
$\omega_{\max\text{-est-2}} \in R^3$ = estimated maximum satellite's attitude rate after stop of robot-arm motion
$\omega_o$ = orbital rate of the satellite
$\omega_{\mathrm{offset}} \in R^3$ = satellite attitude rate that the gains scheduling starts
$\omega_s \in R^3$ = satellite's angular rate

## Introduction

WHEN a robot arm moves on a satellite to conduct some tasks, the robot arm generates a reaction torque to the satellite platform. Because transmitting command, telemetry data, and video images to/from the robot satellite from/to an onground control station needs a communication link with relatively wide bandwidth, the attitude of the satellite platform and the direction of the intersatellite communication antenna must be precisely controlled. Most satellites have a satellite attitude control system to maintain the satellite attitude against the disturbance torque imposed by the Earth's gravity field, the atmospheric pressure, etc. However, the torques from these disturbance sources are small. On the other hand, the reaction torque from the robot-arm motion is large and produces large attitude error even if the robot arm is working properly.

There are many studies on the dynamics and control of root satellites. References 1 and 2 summarize those studies. Studies may be grouped into two categories. The first category consists of studies on the dynamics of a satellite with a robot arm while the satellite attitude is not actively controlled.[3–7] The main interests of these studies are in areas such as how to minimize the satellite attitude error or how to direct the satellite attitude by the robot-arm motion. However, satellite attitude control is necessary to maintain the communication link while a robot arm works. Free satellite motion without active attitude control is only preferred when a robot arm grasps an object that is free floating against the satellite platform that carries the robot. The second category consists of studies on satellite attitude control vs the robot arm's reaction. Most papers[8–10] use feedforward angular momentum compensation to decrease the satellite attitude error while the robot arm works. However, those papers do not consider how to assure the stability of the satellite attitude when a robot arm produces a larger reaction torque.

It is rather easy to predict the motion of the satellite platform vs the reaction torque when the robot arm starts a motion. However, it is not easy to predict the satellite attitude motion after the robot arm stops the motion. It is almost impossible to predict the motion of the robot arm if the robot arm is telemanipulated by an operator. Even if a robot is doing a predefined task, the robot arm has to stop at any time if it detects any danger, such as collision with other object. Stability of the satellite attitude must be guaranteed even against these sudden robot-arm motions.

The author of this paper proposed a coordinated satellite attitude and robot control concept that assures satellite attitude stability while a robot arm woks on a satellite.[11] The essence of the proposed control concept is to maintain the robot arm's angular momentum within the capability that the satellite attitude control system can absorb without producing large satellite attitude error.

These previous discussions were purely theoretical. However, it became a real challenge when the National Space Development Agency (NASDA) launched the Engineering Test Satellite 7 (ETS-VII).[12] ETS-VII carries a 2-m-long robot arm to conduct various tasks. This paper introduces the ETS-VII satellite and the attitude control experiment results on it.

## ETS-VII Satellite

The mission of the ETS-VII satellite was to demonstrate rendezvous docking and space robot technologies. ETS-VII consists of two satellites, the chaser and the target. The mass of the satellites is about 2500 kg and 400 kg, respectively. The satellites were launched

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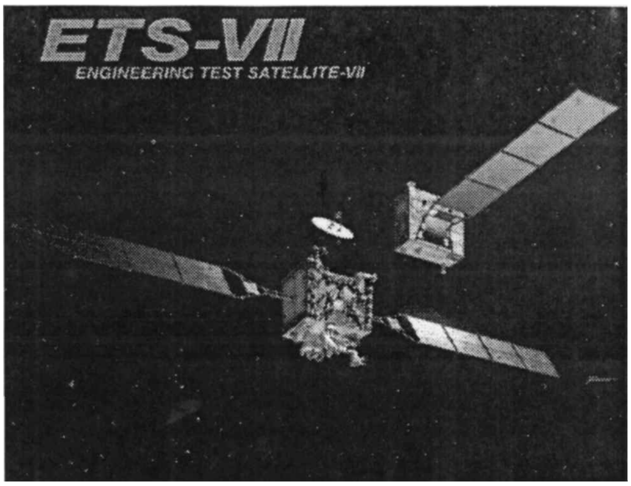


**Fig. 1 ETS-VII chaser (left) and target (right) satellites.**

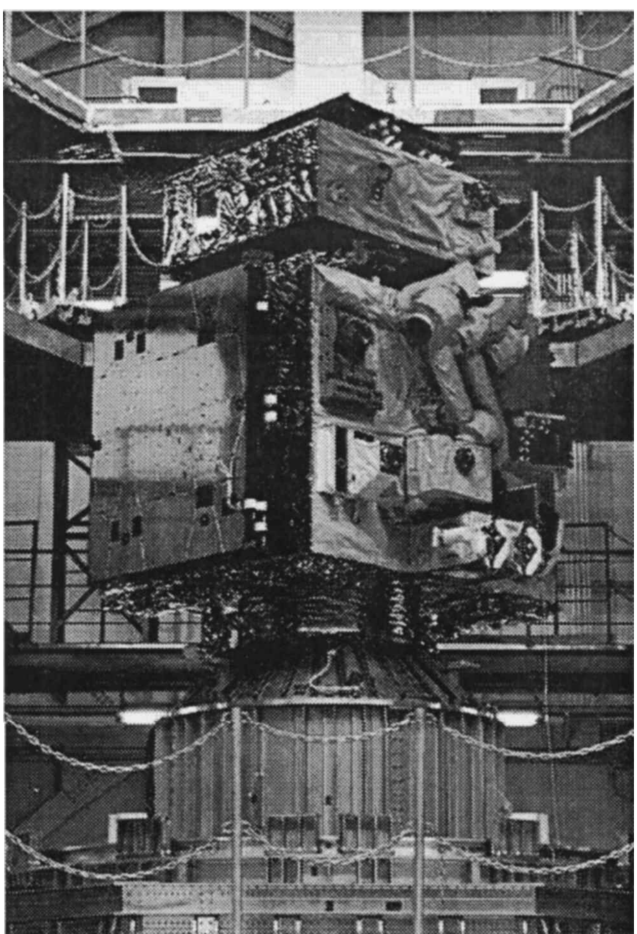

**Fig. 2 ETS-VII chaser (lower) and target (upper) satellites on the H-II rocket (Nov. 1997).**

together by NASDA's H-II rocket on 28 November 1997. The orbit of ETS-VII is 550-km altitude and 35-deg inclination. The target satellite was released from the chaser satellite during the rendezvous docking experiments. During the space robot experiments, the target satellite was connected to the chaser satellite by the docking mechanism. A 2-m-long robot arm was mounted on the chaser satellite and was teleoperated from the onground control station in Japan. An artist image of ETS-VII in orbit is shown in Fig. 1. A photograph of ETS-VII, taken before its launch, is shown in Fig. 2.

**ETS-VII Robot System**

The ETS-VII robot arm has six degrees of freedom (DOF), and its mass is about 150 kg. The mass of the robot arm comes mainly from its six joints, an end-effecter, and cameras. The mass of the links is relatively small (a few kilograms for each). The robot arm and its experimental payloads were mounted on the chaser satellite (Fig. 2). Teleoperation of the onboard robot arm was done in two ways: supervised control mode and telemanipulation mode. In the supervised control mode, instructions from the onground control station to the onboard robot arm are sent by task-level commands such as move from A to B at speed C with payload D. The onboard robot control computer decodes these commands, generates the robot arm's trajectory, and controls the robot arm to realize the instructed robot arm's motion. In the telemanipulation mode, an onground operator uses joysticks to direct the robot arm's motion. Instructions to the onboard robot arm are in the form of robot arm's tip position and attitude every 250 ms. The onboard robot control computer generates the robot arm's trajectory from these data and controls the robot arm to follow the instructions.

**Satellite Attitude Control**

The onboard satellite attitude control system controls the satellite attitude and the direction of the antenna. The Earth sensor and the inertial reference unit are used to measure the satellite attitude motion (the attitude error and the error rate). Three reaction wheels are used to generate control torque to correct the satellite attitude error. Gas jet thrusters are used to desaturate the angular momentum from the reaction wheels and to correct the larger attitude error that the reaction wheels cannot cope with.

The intersatellite communication antenna is mounted on the chaser satellite. The desired direction of the antenna is calculated considering the attitude error of the ETS-VII chaser satellite and the orbital positions of a data relay satellite and the ETS-VII satellite. The onboard attitude control computer manages these satellite attitude and antenna direction controls.

**Onboard Control Systems**

As already mentioned, independent computers perform the satellite attitude and onboard robot-arm controls. Another onboard computer, the guidance and control computer, is used for the rendezvous docking operations. This distributed control approach was selected from the following points of view.

1) The combined DOF of the robot arm (six DOF), the satellite attitude motion (three DOF) and the rendezvous docking (six DOF) are too complicated to be handled by the state-of-art space-borne computers.

2) Satellite attitude control is an already established technology. From a standpoint of cost saving, using the established technology and equipment is preferable.

3) Independent control with minimum interfaces among the other systems has an advantage over the integrated control system from the standpoint that development and testing of individual systems can be done separately and the satellite can be built quickly. This will lead to a faster–better–cheaper mission.

4) Computational requirements from the satellite attitude control, from the robot-arm control, and from the rendezvous docking are different. Requirements from the robot control are tightest, whereas those from the satellite attitude control are moderate, and those from the rendezvous docking are intermediate.

**Coordinated Control System**

Because the separate computers manage controls of the satellite attitude and the robot arm, coordination between these control systems is necessary. It is realized as follows.

The onboard robot control system performs the following functions.

1) It generates the robot arm's trajectory from the robot teleoperation commands that are sent from the onground control station and controls robot arm's joints to realize the trajectory.

2) It estimates the angular momentum that the robot arm will produce during the next attitude control cycle and, if the estimated angular momentum is too large, it stops the robot arm's motion.

3) It provides size of the estimated angular momentum to the onboard satellite attitude control computer.

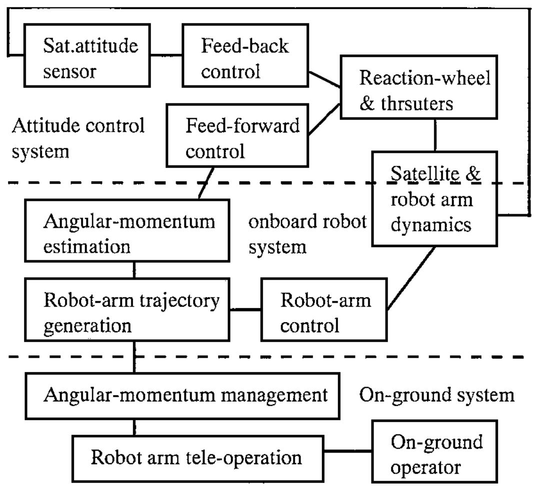


**Fig. 3 Coordinated satellite attitude and robot-arm control system.**

4) It checks the satellite attitude control status, and if the satellite attitude error or the error rate is large, it inhibits the robot arm's motion.

The onground robot control system performs the following functions.

1) It plans tasks for the robot arm and generates the robot teleoperation commands.

2) It checks the robot teleoperation commands to ensure that they will not generate more angular momentum than the satellite attitude control system can absorb. If the commands are too large, it rejects sending them or modifies them.

3) It monitors motion of the onboard robot arm and the satellite platform.

The onboard satellite attitude control system performs the following functions.

1) It measures the satellite attitude error and the error rate.

2) It controls the satellite attitude using the reaction wheels and the gas jet thrusters to keep the attitude error and the error rate within the required limit.

3) It calculates the direction of the data relay satellite and directs the communication antenna to that direction.

4) It receives the estimated angular momentum of the robot arm's motion from the onboard robot control computer and conducts the feedforward angular momentum cancellation.

The onground satellite attitude control system (part of the satellite tracking and control system) performs the function of monitoring the satellite. (In nominal situations, control of the satellite attitude is a function of the onboard satellite attitude control system. In case of malfunctions, the onground control system sends necessary commands to save the satellite.)

These functions of the onboard and onground control systems are shown in Fig. 3.

### Flexible Appendage

The ETS-VII satellite consists of the chaser and the target satellites, which are connected by the docking mechanism. These satellites have three deployed solar arrays, one communication antenna on a gimbaled mast, and a 2-m-long robot arm. These are considered as the flexible appendages. Major resonance frequencies of these flexible appendages were estimated as follows during the development phase of the satellite: 1) solar panels of the chaser satellite, out-of-plane bending of 0.33 Hz and in-plane torsion of 0.91 Hz; 2) solar panel of the target satellite, out-of-plane bending of 0.52 Hz and in-plane torsion not available; 3) robot arm at standby position over 1.0 Hz and in a stretch pose over 0.1 Hz; and 4) antenna mast over 1.0 Hz.

The first-order out-of-plane bending of the chaser satellite's solar panel is the lowest resonance frequency if the robot arm is in a nominal operation pose. However, its frequency is well separated from the bandwidth of the satellite attitude control system, which is lower than 0.1 Hz. The resonance frequencies of the robot arm and the antenna are higher than this.

## Experiment Results

### Experiment Plan

Many experiments were conducted on ETS-VII, such as rendezvous docking and telemanipulation of the onboard robot arm. However, this paper is concerned with only the coordinated robot arm and satellite attitude control experiments. The experiments were conducted as follows: 1) identification of the dynamics characteristics of the satellite; 2) coordinated satellite attitude control experiments, which absorb the robot arm's reaction; 3) coordinated robot arm control experiments, which will not generate excess satellite attitude disturbances; and 4) robot-arm control experiments while the satellite attitude is in free motion

### System Identification

In analyzing the dynamics and control of a satellite, the moment of inertia (MOI) of the satellite and the resonance frequency of the flexible appendages are important parameters. However, these parameters are difficult to measure in the gravity field on Earth. Therefore, identification of these parameters was done inorbit.

Figure 4 shows the estimated angular momentum of the robot-arm motion around the roll axis of the satellite, $H_{\mathrm{RBT}-x}$, the satellite attitude rate (roll rate), and the reaction wheel's angular momentum $H_{\mathrm{RW}-x}$ vs the robot arm's motion.

The robot arm's motion generated the angular momentum of about 10 N · ms at its peak. The angular momentum accumulated from the natural environmental disturbance torque is relatively small. For example, in Fig. 5, the angular momentum, which is accumulated from the natural environmental disturbance torque for a time period of 1600 s is about 1 N · ms. On the other hand, robot-arm motion generated more than 1.5 N · ms in a few seconds. Therefore, the angular momentum conservation law is applicable in a relatively short time period, such as 30 s (Fig. 4). From Fig. 4, it can be seen that the reaction wheel is working at its full capability between 495 and 520 s, and the maximum output torque is 0.12 N · m (=3.0 N · ms/25 s). From the satellite attitude motion in this period, the moment of inertia of the satellite around the $X$ axis, $I_{\mathrm{sat}-x}$, can be calculated as follows assuming the angular momentum of the robot, $H_{\mathrm{RBT}}$, is equal to the sum of the angular momentum of the satellite platform ($H_{\mathrm{sat}} = I_{\mathrm{sat}}\ \omega_s$) and that of the reaction wheel, $H_{\mathrm{RW}}$:

$$I_{\mathrm{sat}-x} = (H_{\mathrm{RBT}-x} - H_{\mathrm{RW}-x})/\omega_{s-x} = 6500\ \mathrm{kg\ m}^2 \qquad (1)$$

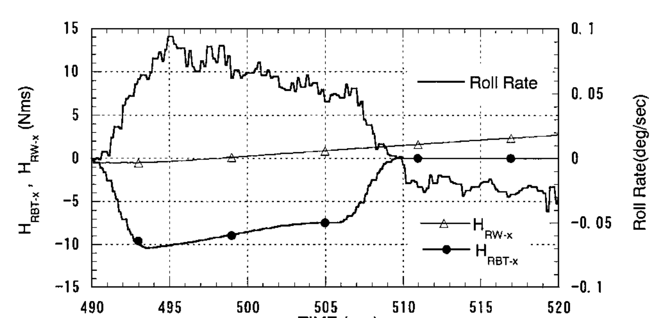


**Fig. 4 Estimation of MOI and natural frequency of the flexible appendage.**

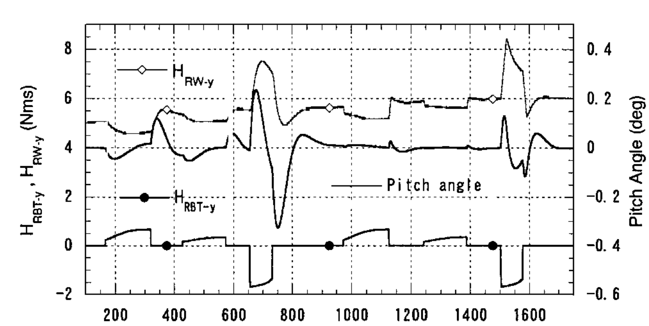


**Fig. 5 Feedback control and the coordinated control vs robot arm's reaction.**

This estimation agrees well with what was predicted by the analysis during the satellite design phase. MOIs in other axis were also estimated and showed good agreement with the prediction. (Note that, because estimations of these satellite parameters in this section are calculated from the readings of the graphs of Figs. 4 and 5, estimation error of $\pm 10\%$ would be included.)

The resonance frequency of the flexible appendage can be obtained by fast Fourier transform analysis of the satellite attitude rate data of Fig. 4. The first-order out-of-plane bending of the solar panel is the lowest resonance mode and was measured as 0.35 Hz. Because the data predicted in the design phase were 0.33 Hz, this measurement agrees quite well with the designed data. Details of this experiment are shown in Ref. 13.

**Coordinated Satellite Attitude Control**

When the coordinated satellite attitude control is activated, the angular momentum of the robot arm is estimated by the onboard robot control computer and is sent to the satellite attitude control computer. The satellite attitude control computer then conducts the feedforward angular momentum cancellation in addition to traditional feedback control. Three reaction wheels are used as the attitude control actuators when the robot-arm motion is moderate. The gas jet thrusters are used when the robot arm motion generates larger angular momentum than the reaction wheels can absorb.

Figure 5 shows the satellite attitude motion (pitch angle) vs the robot arm's angular momentum $H_{RBT-y}$ and the angular momentum of the pitch reaction wheel, $H_{RW-y}$. Satellite attitude control in the first-half period until 900 s was by the feedback reaction wheel control, and in the latter-half period, after 900 s, was by the coordinated reaction wheel control. The robot arm made the same sequential motion in these two attitude control modes. The coordinated control shows better attitude control performance than the feedback attitude control.

Similar experiments were conducted when the gas jet thrusters are used. Figure 6 shows the attitude motion of the chaser satellite when the robot arm grasped the target satellite and moved it forward and backward. Conventional feedback control was used until 1100 s, and then coordinated control was used. The satellite's attitude error became about 1/10 by use of the coordinated control.

**Coordinated Robot-Arm Control**

The feedforward angular momentum cancellation demonstrated better satellite attitude control performance, as described in the preceding section. However, we should note that feedforward control does not necessarily guarantee better satellite attitude control performance. Figure 7 shows an example. The robot arm moved the same trajectory as in the case of Fig. 5 but at twice the speed. Feedback control was used until 650 s and then the feedforward angular momentum cancellation was added while the same robot-arm motion was repeated. The satellite attitude error became larger after stopping the robot arm's motion at around 1150 s.

This can be explained using Figs. 8 and 9, which show typical satellite attitude motion vs the robot arm's reaction in the phase plane. The horizontal axis shows the satellite attitude error, and the vertical axis shows the attitude error rate. Because Figs. 8 and 9 show just the tendencies of the satellite attitude motion by the robot arm motions, vibrations of the flexible appendages are not considered.

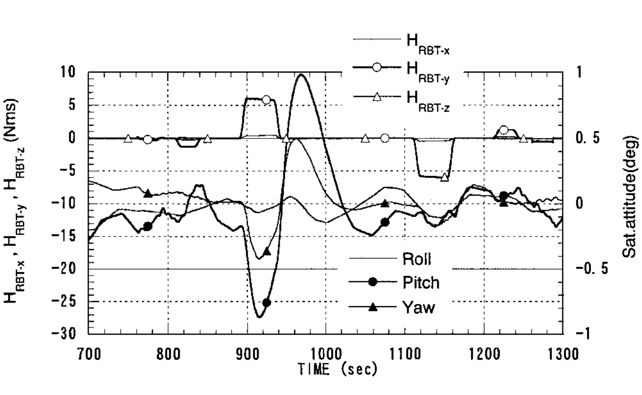


**Fig. 6 Satellite attitude while the robot arm handles the target satellite.**

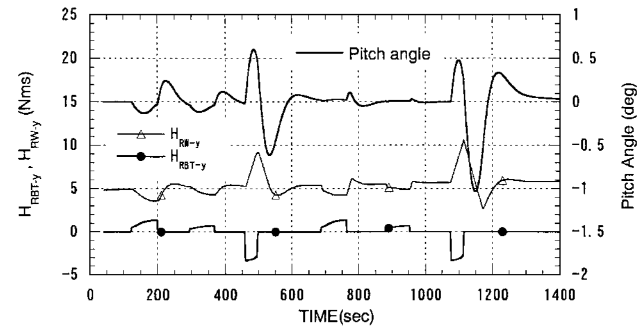


**Fig. 7 Satellite attitude motion when the robot arm's speed is twice that shown in Fig. 5.**

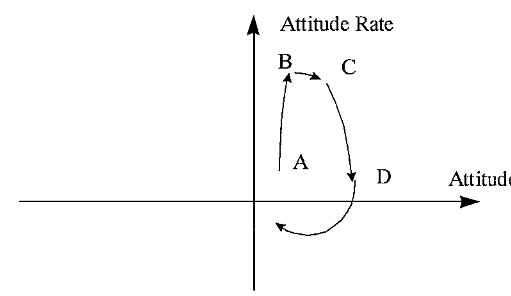


**Fig. 8 Satellite attitude motion vs robot arm's motion (short duration).**

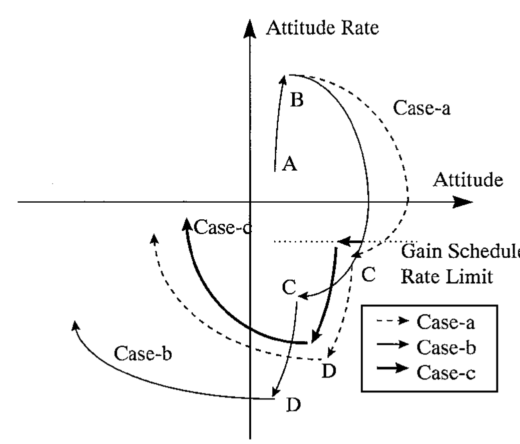


**Fig. 9 Satellite attitude motion vs robot arm's motion (long duration).**

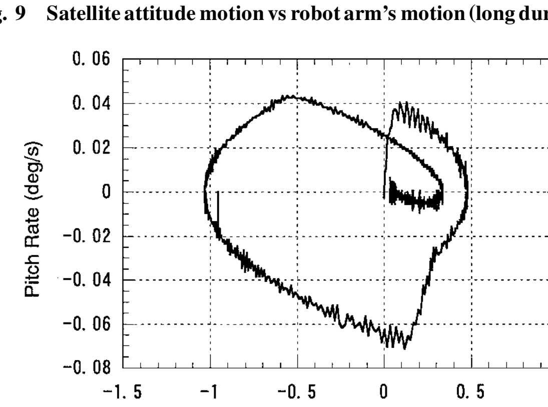


**Fig. 10 Satellite attitude motion when the robot arm motion is beyond the capability of the coordinated satellite attitude control.**

The satellite attitude motion in a phase plane during the time period of 1050–1400 s (Fig. 7) is shown in Fig. 10. Because it is difficult to estimate precisely the robot arm's reaction torque and to cancel it accurately without time delay, the robot arm's reaction torque that is not canceled is stored on the satellite body as the angular momentum and produces the satellite attitude error rate (satellite body rate). A–D in Figs. 8 and 9 show the timings just before the start of the robot arm's motion, just after start, just before stop, and just after stop, respectively. Lines A–B and lines C–D are mainly the robot arm's reaction, and lines B–C show the satellite attitude control effort. Case a of Fig. 9 shows the feedback control case, and case b shows the coordinated control case. The initial conditions of Fig. 8 and cases of Fig. 9, such as the initial satellite attitude, attitude rate, and robot arm's speed, are same. The difference is just the duration of the robot arm's motion. The robot arm has to stop at any time if it has a collision or other problems that restrain its operation. If the robot arm is telemanipulated by an onground operator, a move-and-wait motion may be conducted to overcome the time delay. Figure 9 shows that the satellite attitude error may become larger after the stop of the robot arm's motion if the robot arm's reaction acts in concert with the satellite attitude control effort. This tendency becomes apparent in the feedforward control case.

To prevent the satellite attitude error from becoming too large, beyond the capability of the satellite attitude control system, such as the linear range of the satellite's attitude sensor or the tracking capability of the data relay antenna, ETS-VII's onground and onboard robot control system conduct coordinated robot control. This coordinated robot control is realized by estimating the angular momentum of the planned robot-arm motion. If the planned robot-arm motion will produce a larger angular momentum than the satellite attitude control system can absorb in a reasonable time, then such a robot arm motion will be rejected or modified into a moderate motion. Details of this angular momentum management strategy are discussed in Ref. 11.

**Gain Scheduling Control**

The coordinated satellite attitude control, shown in Figs. 5 and 6, demonstrates good attitude control performance if the robot arm motion is managed moderately. Figure 7 showed the limitation of coordinated satellite attitude control. Coordinated robot-arm control is to limit the robot arm motion within the capability of coordinated satellite attitude control. However, this tends to impose a strict restriction on the robot-arm motion when reaction wheels are used as the attitude control actuators. In the case of the ETS-VII satellite, the maximum robot arm's tip speed was limited to about 15–20 mm/s depending on the direction and duration of the robot-arm motion. Therefore, patience was required when the robot arm made a large motion.

Because the satellite attitude error tends to become large after stopping the robot-arm motion when the robot arm's reaction acts in the same direction that the satellite attitude control system is driving the satellite platform, gain scheduling control was introduced to reduce the large satellite attitude error after stop of the robot-arm motion.

In this control mode, the control gain of the satellite attitude control system to drive the reaction wheel or the gas jet thrusters is set to zero if the robot arm is moving and the satellite attitude motion is in the second or fourth dimension in the phase plane of Fig. 9. The control gain is reset to the original value when the robot arm stops its motion. This is to restrict the satellite attitude rate from becoming large before the robot arm stops. This control concept is shown in Fig. 9 as case c. The gain scheduling start line is slightly offset from the zero satellite attitude rate line to avoid the influence of the vibration of the satellite's flexible appendages.

The satellite attitude motion in the gain scheduling control mode is shown in Fig. 11. The robot arm made the same motion shown in Fig. 7. The satellite attitude control mode until 1250 s was the gain scheduling control with the feedback/feedforward control, and then gain scheduling control without feedforward control (feedback control only) was used. The reaction wheels were used as the satellite attitude control actuators in this experiment. Figure 11 shows that the satellite attitude stability is improved by introducing gains scheduling control. Note that gain scheduling control without the feedforward control (feedback control only) showed fairly good control performance, whereas gain scheduling control with feedback and feedforward control showed better performance. Because gain scheduling control without feedforward control (feedback control only) does not need high computation power, this would be a reasonable solution for the robot satellite's attitude control system, although the gain scheduling feedback/feedforward control is desirable.

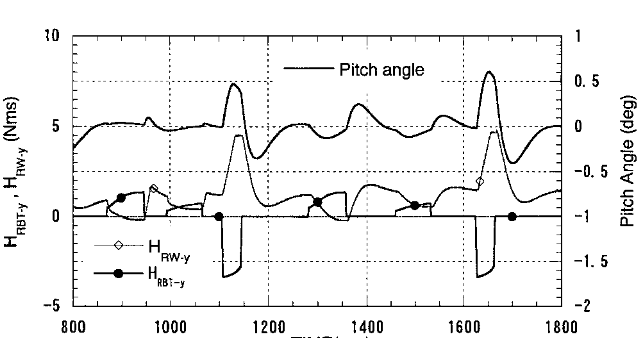


**Fig. 11 Satellite attitude motion with gain scheduling control.**

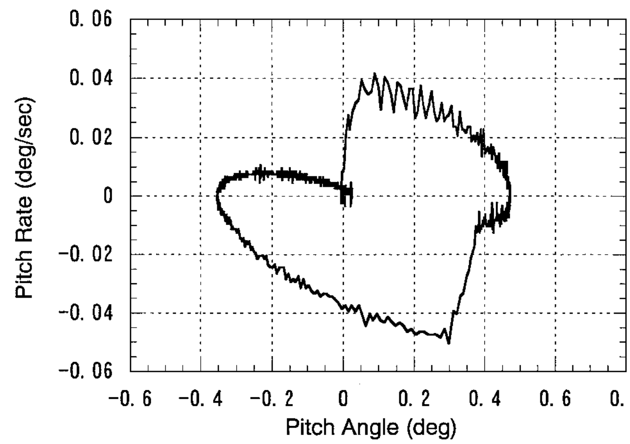


**Fig. 12 Satellite attitude motion during the time period of 1610–1800 s of Fig. 11.**

Gain scheduling control has another advantage in coordinated robot-arm control. In the feedback control mode or in the feedback and feedforward control mode, the maximum angular rate of the satellite platform before the robot arm stops its motion is difficult to predict. This causes a strict restriction on the robot-arm motion by the coordinated robot-arm control. In gain scheduling control, the maximum angular rate of the satellite platform is easily determined by the maximum angular momentum of the robot-arm motion and the initial attitude rate of the satellite platform. Therefore, to assure the stability of the satellite platform, the coordinated robot-arm control should maintain the angular momentum of the robot arm motion in each satellite body axis ($i = x, y, z$) as follows:

$$|\omega_{\text{max-est-1-}i}| = |H_{\text{RBT-}i} / I_{\text{sat-}i} + \omega_{\text{init-}i}| \leq \omega_{\text{max-}i} \tag{2a}$$

$$|\omega_{\text{max-est-2-}i}| = |H_{\text{RBT-}i} / I_{\text{sat-}i} + \omega_{\text{offset-}i}| \leq \omega_{\text{max-}i} \tag{2b}$$

Figure 12 shows the satellite attitude motion in the phase plane during the time period of 1610–1800 s of Fig. 11. Because robot-arm motion shown in Figs. 7 and 11 or Figs. 10 and 12 are the same, it is apparent that the introduction of the gain scheduling control improved the satellite attitude stability against the robot arm's motion. The slight difference between Figs. 9 and 12 (pitch rate in Fig. 12 is not constant when control gain is set to zero) is because the angular momentum of the robot-arm motion is not constant in Fig. 12, whereas in Fig. 9 it is assumed there is constant angular momentum during the robot-arm motion.

**Free-Motion Satellite**

There are many papers that discuss robot motion on a free-motion satellite, a satellite without active satellite attitude control. Similar experiments, to control the robot arm while the satellite attitude control is disabled, were tried on ETS-VII. However, it was not easy to keep the satellite attitude error within a few degrees for more than 5–10 min. This was because the gravity-gradient torque and the residual angular momentum of the reaction wheels became major disturbance sources that caused large attitude error.

Satellite attitude motion vs disturbance torque and the angular momentum of the satellite is expressed as follows:

$$\frac{\mathrm{d}\boldsymbol{H}_{\mathrm{sys}}}{\mathrm{d}t} = \boldsymbol{T}_d - \omega_o(\boldsymbol{H}_{\mathrm{sat}} + \boldsymbol{H}_{\mathrm{RBT}} + \boldsymbol{H}_{\mathrm{RW}}) \quad (3)$$

Other environmental torque, such as solar pressure torque, is negligibly small in the case of ETS-VII. Most textbooks on satellite attitude control discuss the gravity-gradient torque assuming the satellite is symmetric in its mass distribution. In such a case, the gravity-gradient torque $T_g$ depends on the satellite attitude error and can be neglected when the attitude error is small:

$$\boldsymbol{T}_g = (3\mu/R^3)\begin{bmatrix}(I_z - I_y)\phi \\ (I_z - I_x)\theta \\ 0\end{bmatrix} \quad (4)$$

However if the satellite is not symmetric, the gravity-gradient torque is expressed as follows:

$$\boldsymbol{T}_g = (3\mu/R^3)\boldsymbol{E} \times I_{\mathrm{sat}}\boldsymbol{E} \quad (5)$$

If the product of inertia of $I_{\mathrm{sat}}$ is not small, the gravity-gradient torque becomes not negligible. Equation (3) also shows that if there is some angular momentum in the reaction wheels, it produces the torque against satellite in the other body axis. To realize stable free satellite motion, the angular momentum of the reaction wheels must be discharged, and the residual angular velocity of the satellite platform must be removed. Otherwise, satellite attitude error will quickly grow by the residual angular momentum or the residual attitude rate. However, it is not easy to remove all residual angular velocity of the satellite platform before switching off the gas jet thrusters. The reaction wheel must be used to remove the residual angular momentum from the satellite platform, and therefore, some level of angular momentum remains in the reaction wheel. Several trials were conducted during the experiments on ETS-VII to realize stable free satellite motion. However it was not easy to keep the residual angular momentum of the reaction wheel below 1 N · ms. The products of the inertia of the ETS-VII satellite changed depending on the posture of the robot arm and caused the gravity-gradient torque. This residual angular momentum and the gravity-gradient torque drove the satellite platform out of the stable condition, and the free satellite attitude motion could not be continued for more than 5–10 min.

## Conclusions

This paper introduced experiment results in satellite attitude control of a robot satellite on which a robot arm works. NASDA's ETS-VII satellite is the world's first satellite on which a robot was operated. To stabilize the ETS-VII satellite against the robot arm's motion, conventional feedback control, feedback control with feedforward angular momentum compensation (coordinated satellite attitude control) and coordinated robot-arm control were tested. The in-orbit tests of these control methods showed their usefulness and also showed their limitations. It was also shown that the gain scheduling of the satellite attitude control system can further reduce the satellite attitude error that is caused by the robot-arm motion. Dynamic characteristics of the satellite and its flexible appendages were also investigated using the robot arm. It is also shown that the free satellite attitude motion is neither preferable nor easy to realize due to the disturbance torque caused by the product of inertia and the residual angular momentum of the reaction wheels.

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