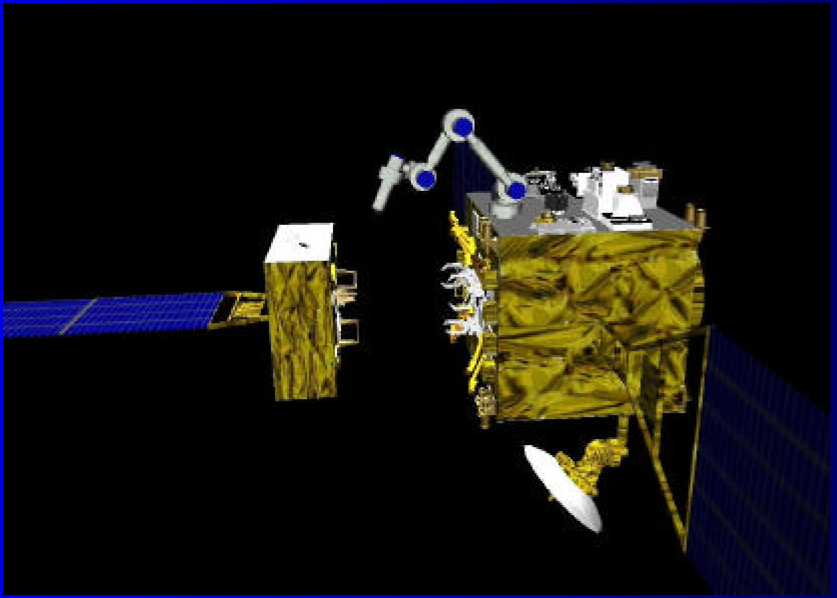
Zero Reaction Maneuver:
Flight Validation with ETS-VII Space Robot
and
Extension to Kinematically Redundant Arm



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Outline of the Talk

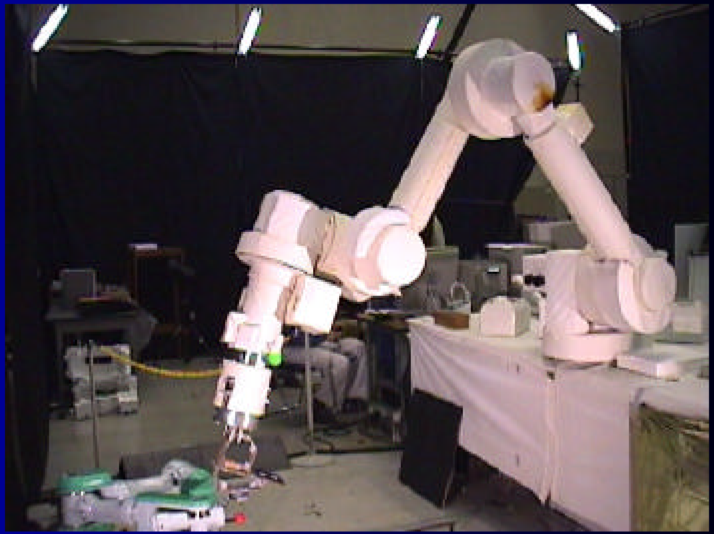
- ETS-VII: the Engineering Test Satellite
- Extended Flight Experiment Opportunity
- The Zero Reaction Maneuver
- Preparation and Flight Data
- Extension to a Redundant Arm
- Conclusions

ETS-VII: the Engineering Test Satellite

(Mission by National Space Development Agency, NASDA, Japan)

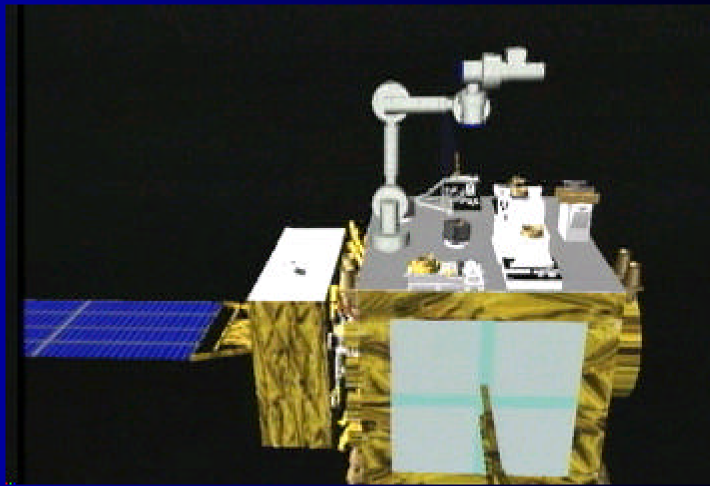
- **Purpose:**
  Study and demonstrate robotics capability for orbital missions and autonomous RVD technology
- **Feature:**
  A 2m-long, 6 DOF manipulator arm is mounted on an unmanned base satellite. A sub-satellite is separated for the RVD experiments.
- **Mission:**
  Launched on Nov. 28, 1997, the mission successfully completed by the end of 1999.

The Manipulator Arm



- 6 DOF, 2m
- DC blushless motors
- Harmonic Drive gear train
- 1.3 mm positioning accuracy at endtip
- 50 mm/s, 5 deg/s velocity at endtip
- More than 40N force, 10Nm torque at endtip
- Designed and manufactured by Toshiba Co.

Robotics Experiments



- Autonomous exchange of ORUs.
- Dexterous operation such as a peg-in-hole task.
- Teleoperation from a ground station via TDRS.
- Assembling components.
- Deploy and retrieve a space structure.
- Capture and berthing of a target satellite.
- Dynamics and control of a free-flying multibody system.

The Extended Flight Experiment Opportunity

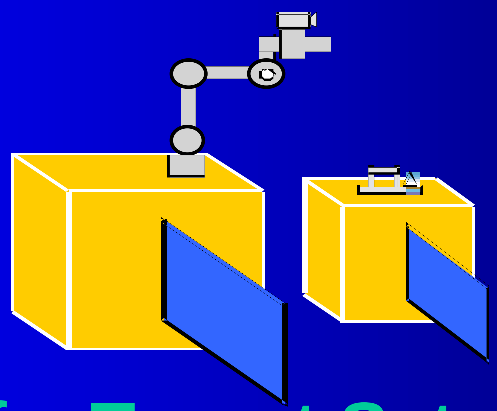
- After the successful mission completion at the end of May 1999, the extended flight experiment opportunity was opened for academic researchers.
- Unique opportunity for space robotics community
- AO released in Feb 1999

→ Four laboratories applied

Tohoku Univ. (2), Tokyo Inst. Tech, Kyoto Univ.

Flight Experiments to Verify Dynamics and Control of Free-Flying Space Robot for Future Satellite Servicing

- Extension of mission life by Refueling and Refurbishment
- Retrieve, Re-orbit, Replace and/or Repair of a malfunctioning or end-of-life satellite

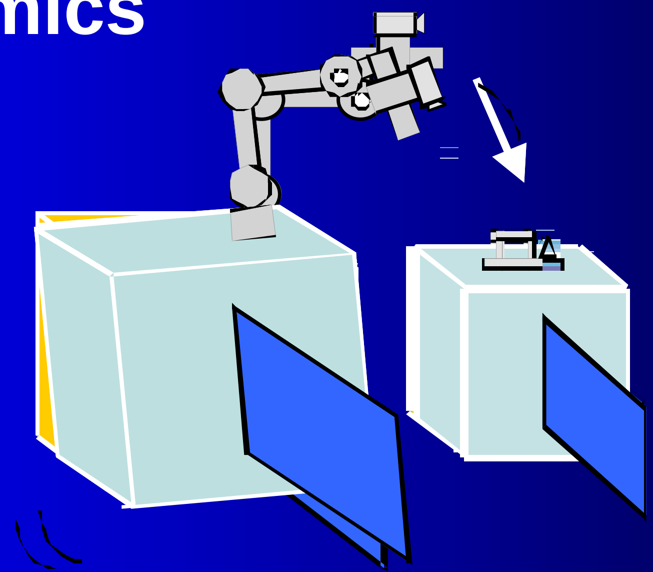


Capture of a Target Satellite

Fine and Dexterous On-board Manipulation

Dynamics and Control Issues for a Free-Flying Space Robot

Interaction Between Satellite (Attitude) Dynamics and Robot Dynamics



Robot Control taking account the Reaction Dynamics

The Experiments

for the study of Reaction Dynamics

1. Manipulator operation that yields minimum reaction on the base satellite

   Reaction Null-Space

   Zero Reaction Maneuver

2. Manipulator endpoint control for inertial target under the free-floating environmrnt

   Generalized Jacobian Matrix

3. Terminal state control for free-floating space robot

   Nonholonomic Path Planning

4. Base attitude control for quick recovery from the manipulator motion disturbance

   Coordinated Control: an Offset Approach

The Zero Reaction Maneuver: the theory

Momentum Equation:

$$\begin{bmatrix} P \\ L \end{bmatrix} = H_b \dot{x}_b + H_{bm} \dot{\phi}$$

Angular Momentum:

$$\tilde{H}_b \omega_b + \tilde{H}_{bm} \dot{\phi} = L$$

Manipulator Motion that yields Zero Reaction Momentum:

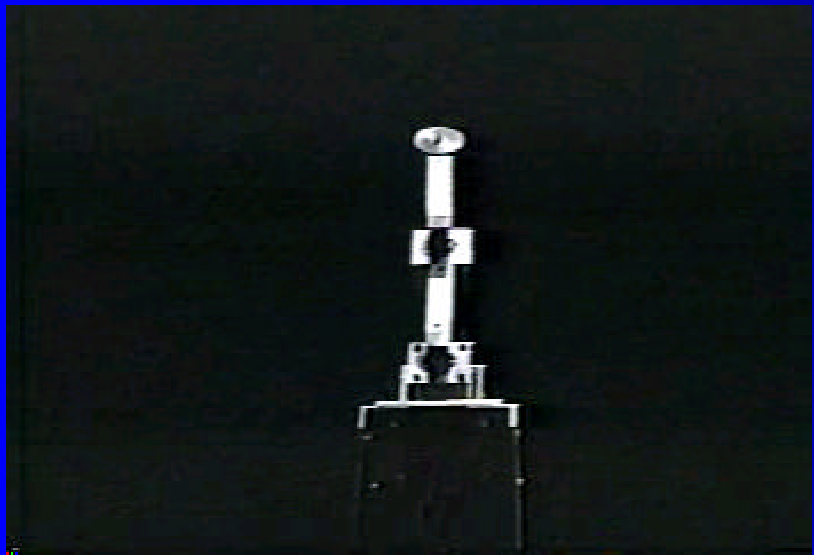
$$\tilde{H}_{bm} \dot{\phi} = 0$$

Solution with Reaction Null Space:

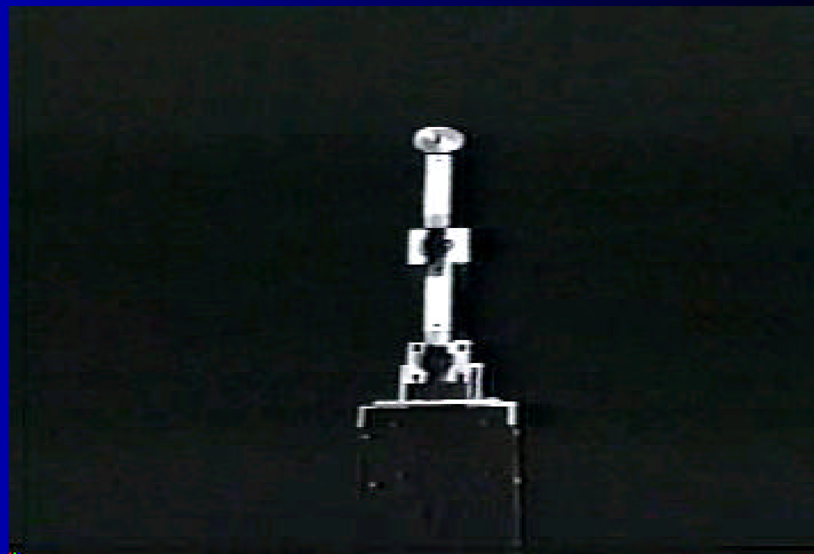
$$\dot{\phi} = (I - \tilde{H}_{bm}^{+} \tilde{H}_{bm}) \dot{\zeta}$$

: Zero Reaction Maneuver

The Zero Reaction Maneuver: Principle Verification



↓ **Zero Reaction Maneuver**



↑ **Conventional Maneuver**

The Zero Reaction Maneuver: Practical Solutions

Zero Reaction Maneuver is possible when the Reaction Null Space exists.

$$\dot{\phi} = (I - \tilde{H}_{bm}^{+} \tilde{H}_{bm}) \, \dot{\zeta}$$

N DOF **N-3 DOF**

N=6 in ETS-VII, the 3 DOF additional constraint introduced.

$$\omega_h = J_\omega \dot{\phi}$$

$$\begin{bmatrix} \tilde{H}_{bm} \\ J_\omega \end{bmatrix} \dot{\phi} = \begin{bmatrix} 0 \\ \omega_h \end{bmatrix}$$

6 DOF **6 DOF**

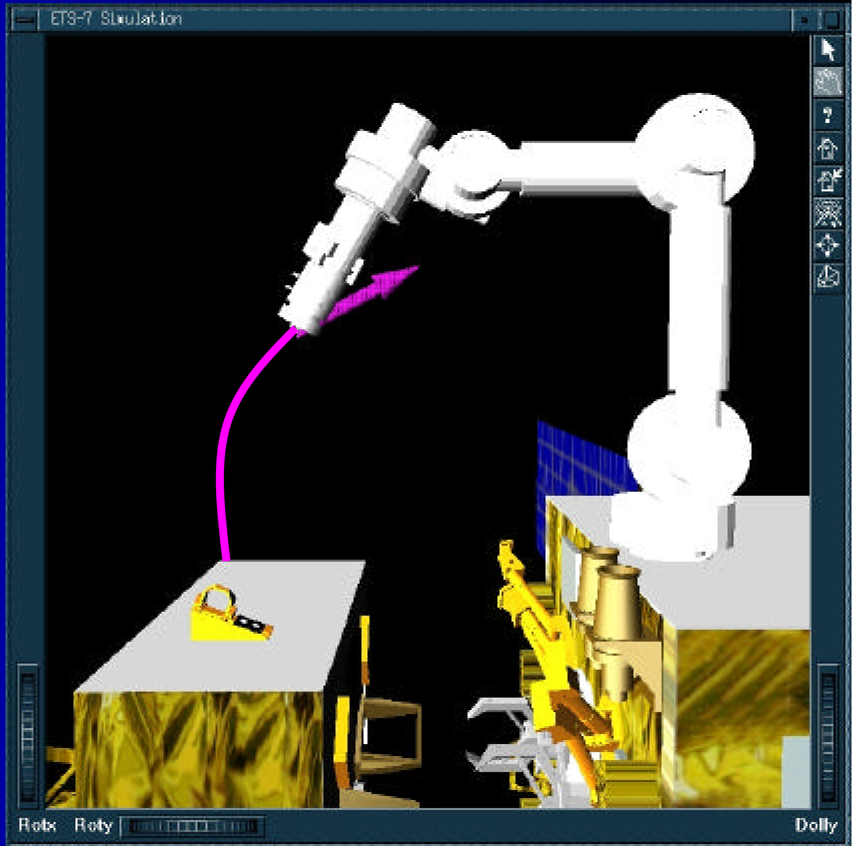
The Zero Reaction Maneuver: Practical Solutions

$$\begin{bmatrix} \tilde{H}_{bm} \\ J_\omega \end{bmatrix} \dot{\phi} = \begin{bmatrix} 0 \\ \omega_h \end{bmatrix}$$

6 DOF **6 DOF**

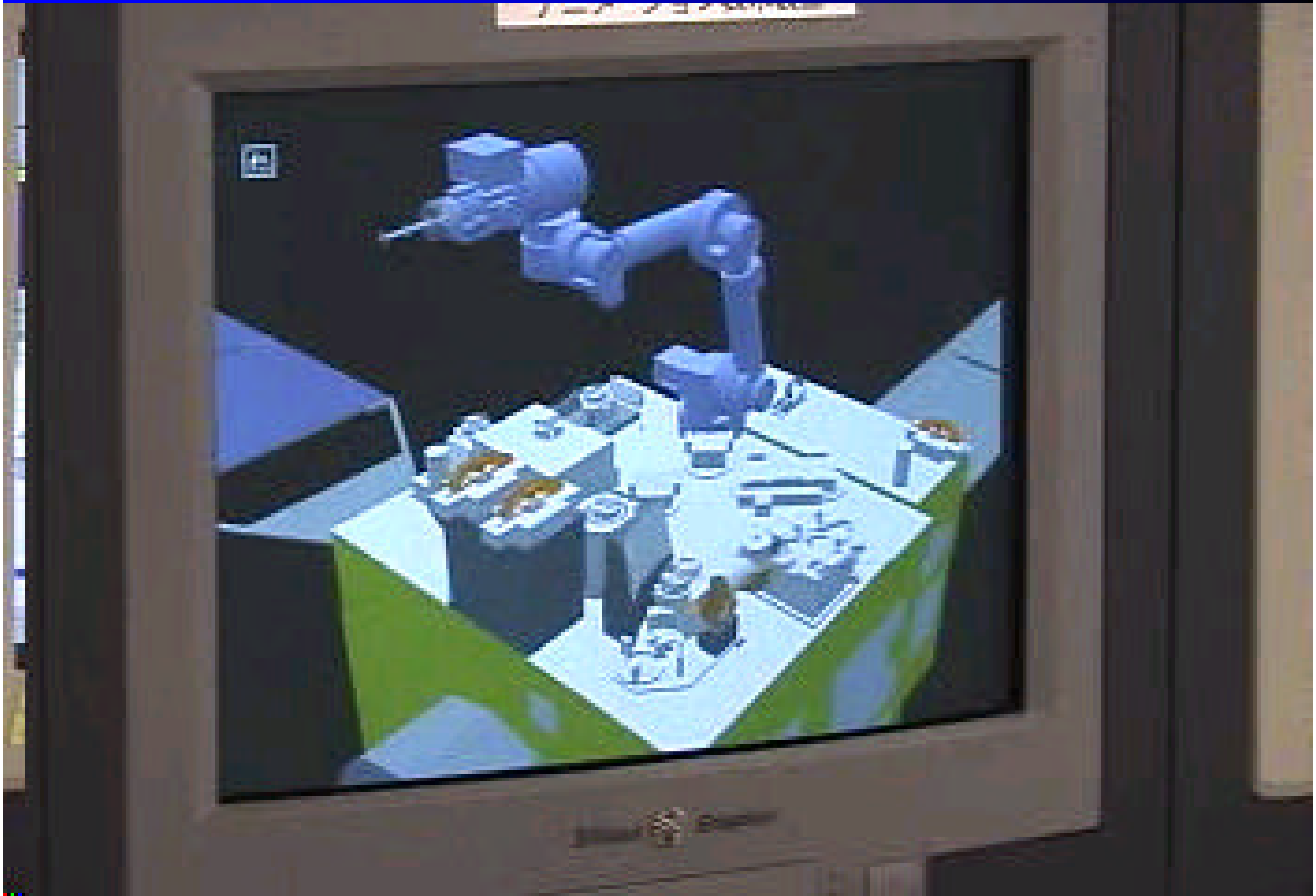
Singularity Consistent Inversion

$$\dot{\phi} = k \bullet \mathrm{adj}\left(\begin{bmatrix} H_{bm} \\ J_\omega \end{bmatrix}\right)\begin{bmatrix} 0 \\ \omega_h \end{bmatrix}$$



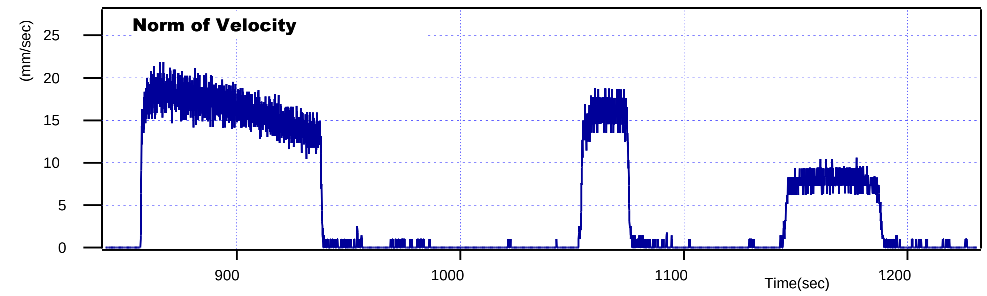
Flight Experiments

- Date： September 30th, 1999
- Time：7h 21m ～11h 25m(JST)
  3 operation windows，total 72 min.
- Manipulator Operation：
  Upload prepared motion trajectory files from the ground in real time. The manipulator arm follows the given trajectory with an on-board servo controller.
- Attitude Mode：
  Selected from (1) feedback control with reaction wheel and (2) free-drift (no control)
- Flight Data：
  Real time telemetry data are recorded.

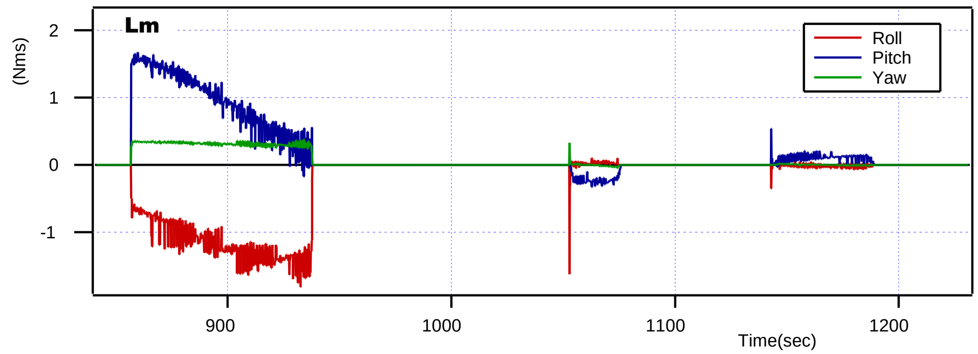


Flight Data: Reactionless Manipulation

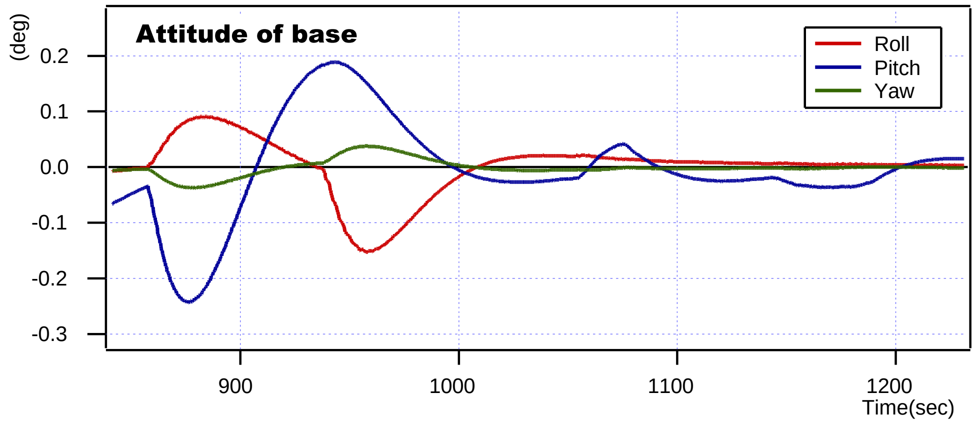
Hand velocity
(m/s)



Reaction momentum
(Nms)



Base attitude
(deg)

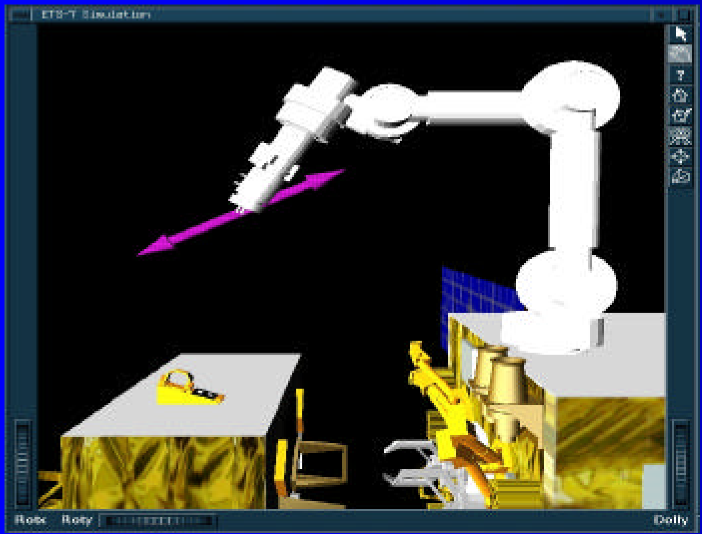


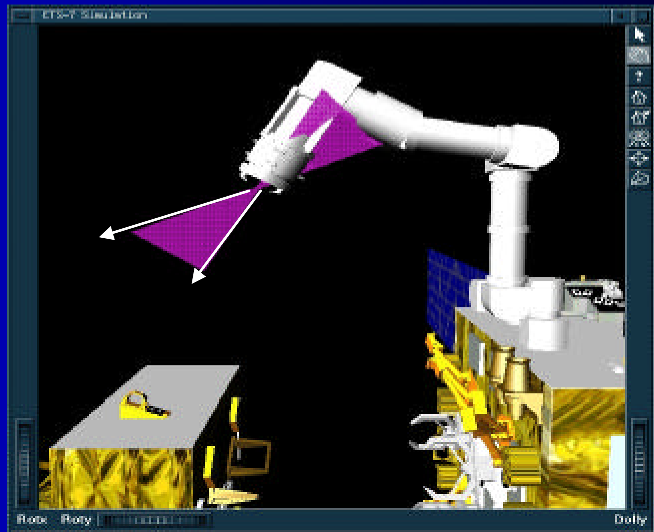
Remarks on the Flight Data

- Zero Reaction Maneuver, or Reactionless Manipulation, yields almost zero reaction on the base.
- Very small reaction is due to the feedback error, or delay, of the joint servo controller.
- With conventional manipulation, the attitude disturbance due to the reaction is significant even though the attitude controlling devices are working.
- Also the attitude recovery time is necessary after the manipulation, which is not needed with Zero Reaction Maneuver.

Limited existence of Zero Reaction trajectory

⇒ Extension to a Redundant Arm





$$\dot{\phi} = G^{+}\begin{bmatrix}0\\ \omega_h\end{bmatrix} + (I - G^{+}G)\,\dot{\xi}$$

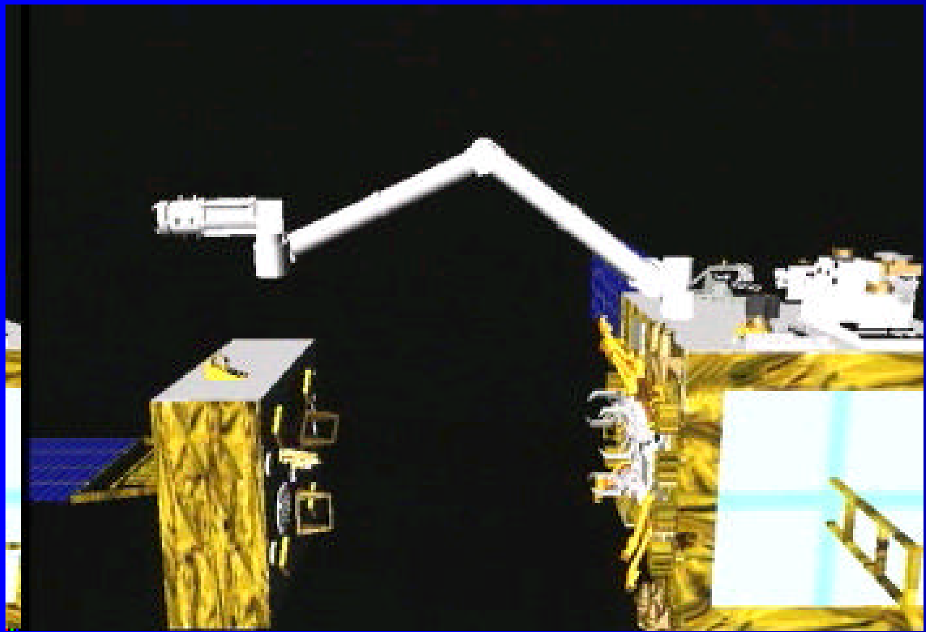
$$G = \begin{bmatrix}H_{bm}\\ J_\omega\end{bmatrix}$$

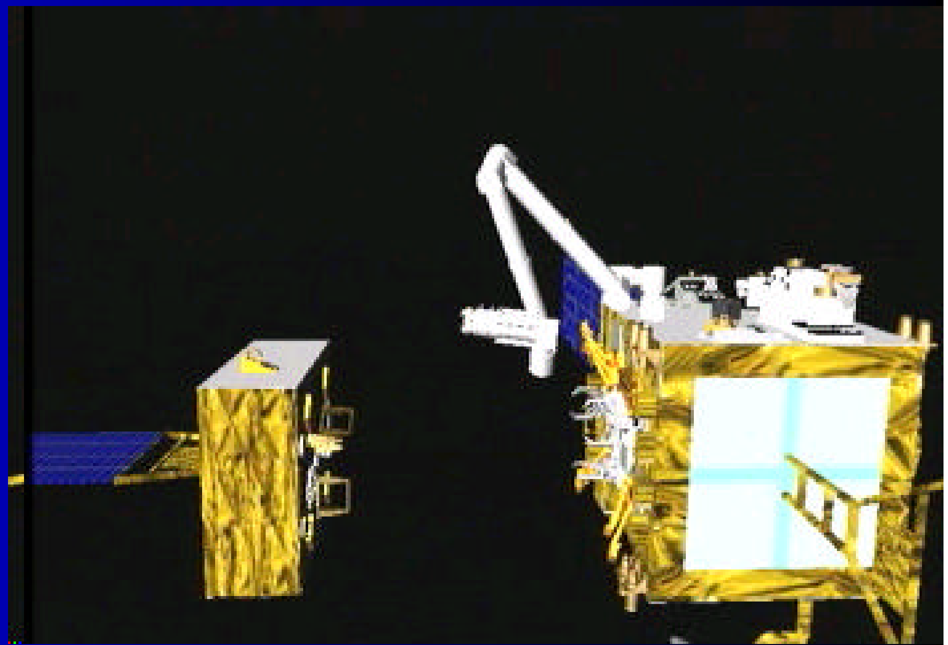
$$\dot{\phi} = (\, I - \tilde{H}_{bm}^{+}\tilde{H}_{bm})\,\dot{\zeta}$$

N DOF **N-3 DOF**

Limited existence of Zero Reaction trajectory

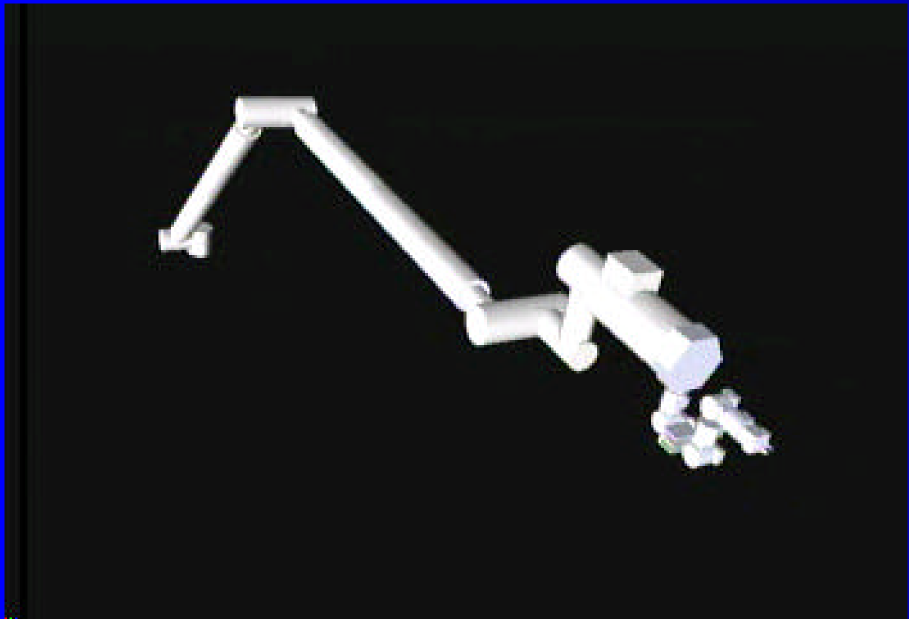
⇒ Extension to a Redundant Arm

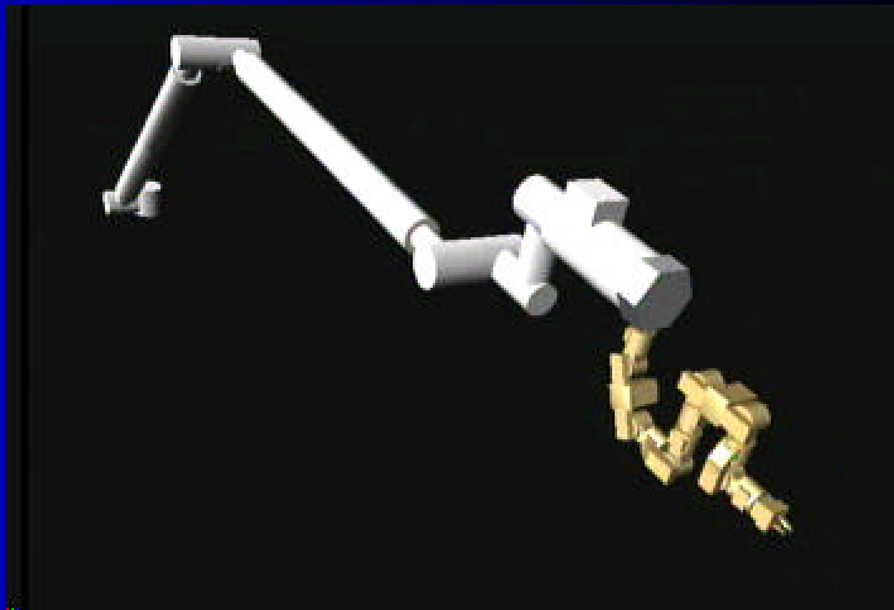




With 7 DOF Arm

Further Application





Macro-Micro manipulator System for Space Station

Conclusions

- Flight experiment on ETS-VII space robot is presented focusing on the Zero Reaction Maneuver (ZRM).
- It is clearly verified that the ZRM yields zero attitude disturbance on the base during the manipulation. The results are very promising to improve space manipulation, saving time for attitude recovery.
- The ZRM trajectory is restrictive with 6 DOF arm, but with a redundant arm more operational freedom is obtained.
- Extensive simulations are carried out for a free-flying space robot and a space station based macro-micro manipulator system.