ANTENNA-ASSEMBLY EXPERIMENTS USING ETS-VII

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ABSTRACT

The construction of large and precise antennas is one of the most important challenges in the development of space infrastructures. Using robots is an effective method for constructing very large and precise antennas in space. The Communication Research Laboratory (CRL) developed an antenna designed to be assembled in space for use in future space communication infrastructures and has been studying teleoperation technologies for controlling space robots. The initial experiments for testing the assembly of this antenna in space are being conducted using Engineering Test Satellite VII (ETS-VII), which was launched in November 1997. ETS-VII-which is the first robotic satellite-was developed by the National Space Development Agency of Japan (NASDA); it is equipped with six-DOF manipulators and antenna-assembling mechanisms developed by the CRL. Here, we briefly describe these experiments, including master-slave experiments using space robots, and our evaluation of the audio feedback system, which uses an eye-mark recorder.

1. INTRODUCTION

Antenna assembly will be an important application of robotics in constructing future space infrastructures. Using robots to assemble antennas is an attractive alternative to using inflatable and deployable antennas as a way to construct large-scale antennas on space stations, space platforms, planetary bases, etc. This is because

(1) they enable antennas to be constructed using prefabricated parts,
(2) they enable antennas to be constructed using a limited number of launchers by reusing the launchers and assembling the antenna in stages,
(3) the sections of the antenna can be easily collimated after they are assembled, and
(4) such antennas can be easily repaired by simply replacing the defective components.

At the Communications Research Laboratory (CRL), we have developed an antenna designed to be assembled in space to investigate the technologies needed for constructing large space antennas[1]-[4]. We are currently testing the assembly of this antenna in space by using Engineering Test Satellite VII (ETS-VII), which is Japan's first robotic satellite. Our aim is to evaluate the mechanisms we designed for achieving sub-millimeter-accuracy assembly and teleoperation. After basic checkout of the satellite, 16 assembly experiments were performed by the CRL in cooperation with the National Space Development Agency of Japan (NASDA). The basic functions of the assembly mechanisms and teleoperation system were confirmed. In this paper, we describe our antenna-assembly experiments using ETS-VII and present some of the experimental results.

2. ANTENNA ASSEMBLY EXPERIMENTS USING ETS-VII

2.1 ETS-VII

ETS-VII is an engineering test satellite developed by NASDA. It was launched aboard an H-II rocket in 1997. It weighs 2.8 t and has a circular orbit with an altitude of 550 km. It was designed to test two technologies-rendezvous docking and space robotics-using a 2-m-long 6-DOF (degrees of freedom) robotic arm. The space robotics experiments included "Advanced Robotic Hand", planned by the Ministry of International Trade and Industry; "Deployable/Detachable Truss Assembly", planned by the National Aerospace Laboratory; and "Experiment on Antenna Assembling Mechanism", planned by the CRL to test mechanisms for assembling structures in space and to study the basic technologies of space robotics needed to assemble an antenna by using a satellite.

The robotic arm is controlled remotely from NASDA's

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Tsukuba Space Center via intersatellite communication through NASA's TDRS. The telemetry information is delivered in 68-byte telemetry packets at 10 Hz through a 9600-bps RS-232C line; it includes the end-effector position, joint angles, force, torque, and status information. Commands for the robotic arm are transmitted at a maximum of 4 Hz through a different 9600-bps RS-232C line. The robotic arm can be moved in not only position-control mode, but also in force-control mode, such as compliance mode or active-limb mode. The time delay (round trip time) is about 6 seconds. Images are obtained by onboard cameras and delivered through two NTSC lines. The images are updated every 2 Hz over each line.

2.2 Antenna-Assembling Mechanism

The antenna-assembling mechanism (AAM) we designed (Fig. 1) consists of three parts: a "Fixed Part (FP)", a "Combining Part (CP)", and a "Catcher for Emergency". The "Fixed Part" and the "Catcher for Emergency" are attached to the outside of the satellite, and the "Combining Part" is connected by a latch to the "Fixed Part". In the experiments, the antenna-assembly process was simulated by disassembling then reassembling the connection between the FP and CP. The CP is captured by the robotic arm by using a grapple. Latching is performed by a very simple motion of the robotic arm. When the latch mechanism is moved straight toward the latch pin, the stopper of a rotary camera, which is moved by a spring, is snapped off and automatically latched. This latching mechanism does not need a power supply, so it has a virtually unlimited lifetime.

To achieve accurate and reliable assembly, the AAM has two adjusting mechanisms. One is a visual guidance mechanism that uses a target mark, and the other is a mechanical guidance mechanism that uses a guide cone (Fig. 1). The image view, which is captured by a camera mounted on the hand of the robotic arm, changes according to the relative drift between the CP and FP. This drift is automatically calculated by analyzing the image of the target mark. The guide cone and compliance mechanism, which is a spring system located between the grapple and the CP, adjust the vibrations between the CP and FP and adjust for the small drift that cannot be handled by the visual guidance mechanism. These mechanisms are important not only for assembly using teleoperation, but also

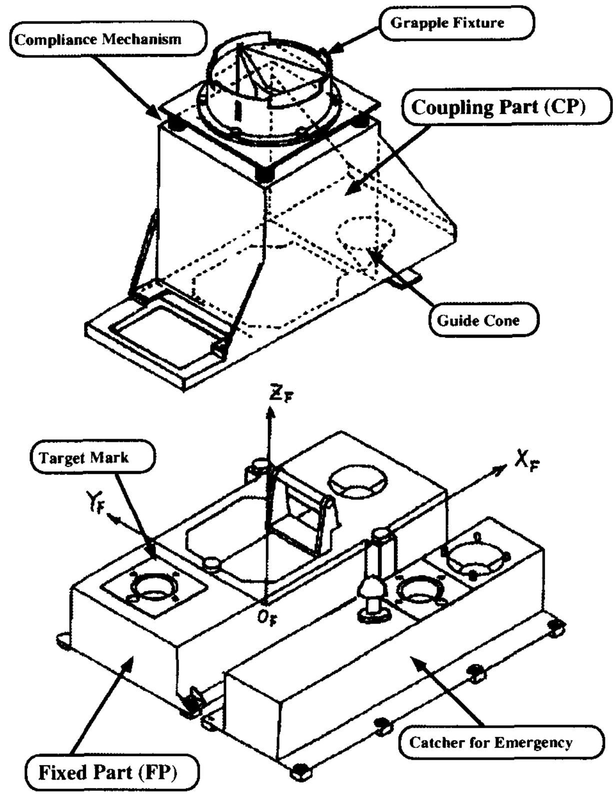

Fig. 1: Antenna-assembling Mechanism (AAM)

for fully automatic assembly.

2.3 Teleoperation system

Given the circumstances under which space robots operate, it is essential to generate motion commands safely and reliably. However, because the duration of each experiment conducted using ETS-VII is limited to 20 minutes by the orbital movement of the satellite, the operator needs to generate motion commands swiftly and efficiently. Therefore, we developed a teleoperation system for our antenna-assembly experiments based on the following considerations in order to achieve reliable and efficient operation (Fig. 2).

1) Semi-automated document processing.
   A macro program written in Japanese is automatically converted to SOP, SOE, robot language, and the language of the operation database.
2) Library of motions
   Verified motions are stocked as parts of the macro language.
3) Multi-modal interface of telemetry data
   Force & tactile (master arm)
   Audio (status: voice, force & torque, motor-noise tone)

Visual (downlinked & processed images, 3D simulation models)

The equipment for the telemetry audio interface is quite simple. An RS-232C interface between the interface computer and NASDA's operations system is diplexed to a personal computer called a telemetry analyzer. When a status change in the telemetry is detected by this analyzer, it gives a spoken warning. The magnitude of force on the end-effector is also presented as a motor-noise tone synthesized by an audio sampler. The operator can thus easily recognize the state of the robotic arm without having to pay much attention to the telemetry display.

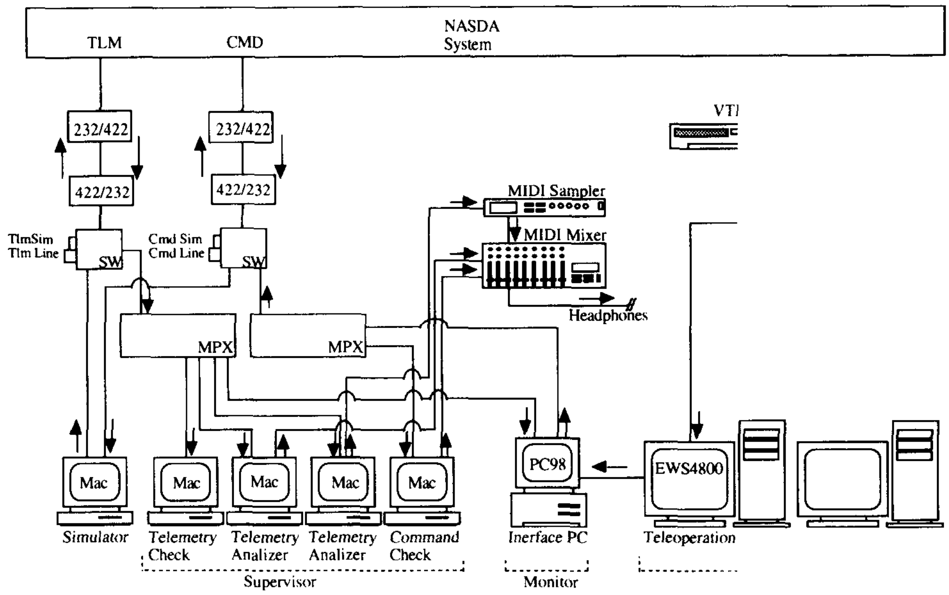

Fig. 2: Teleoperation System

3. RESULTS

3.1 Basic Assembling Process and Assembling in Compliance Control Mode

The basic disassembling-assembling experiments were conducted using the following processes, as illustrated in Figure 3, which shows downlinked images during the experiments. (1) The robotic arm captures the fixture mounted on the AAM-CP (Capture). (2) The rotary cum of the AAM-CP is rotated by a socket wrench installed on the end-effector of the robotic arm (Unlatch). (3) The robotic arm moves the AAM-CP up from the AAM-FP (Disassemble). (4) The robotic arm positions the AAM-CP at the assembly position by using the visual guidance provided by the Target Mark (Position). (5) The robotic arm moves the AAM-CP straight towards the AAM-FP and the latch mechanism automatically connects the AAM-CP to the AAM-FP (Reassemble). (6) The robotic arm releases the AAM-CP fixture (Release).

Figure 4 shows the reactive force at the end-effector of the robotic arm during disassembly and assembly. The AAM was disassembled in about 2430 seconds and reassembled in about 2480 seconds. The assembly was done using very simple operations in which the robotic arm moved the AAM-CP toward the AAM-FP. The AAM was reliably reassembled using a very small force (a maxi-

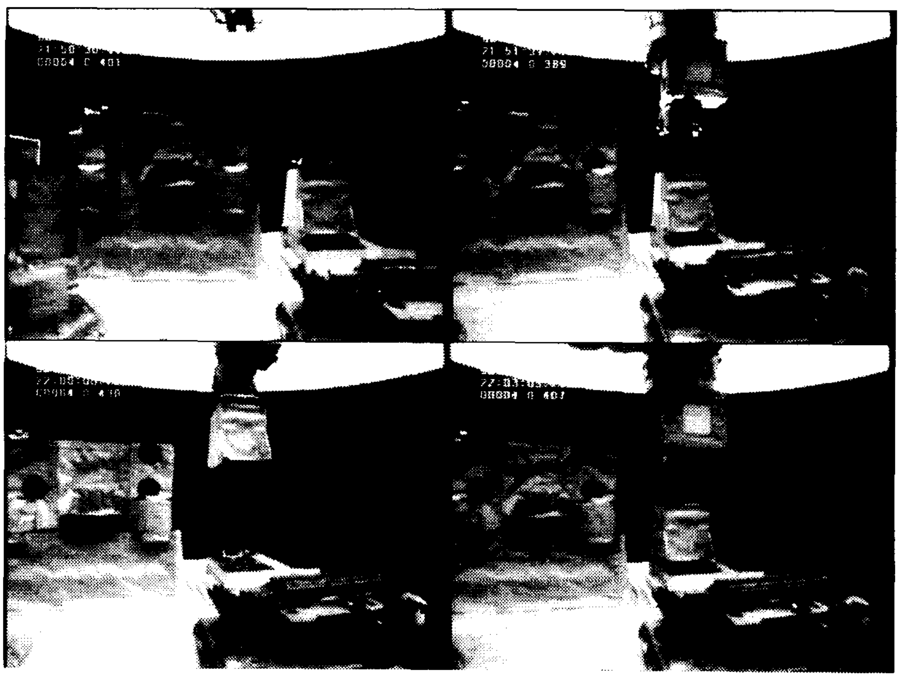

Fig. 3: Downlink Images during assemble-Disassemble Process

mum of 8 N). The disassembly-reassembly process was performed using the satellite 40 times and no mechanical trouble occurred. The mechanical performance of the AAM was very good and did not vary over the year and a half of testing.

3.2 Assembling in Compliance-control and Non-compliance Modes

The robotic arm of ETS-VII supports force feedback control modes, such as compliance-control mode and active-limb mode. In compliance-control mode, the end-effector moves flexibly according to the following control algorithm, which takes into consideration the force and torque at the end-effector.

$$X = F / (MS2 + CS + K)$$

$$R = T / (MS2 + CS + K)$$

The X and R are the shifts in the end-effector, and the F and T are the force and torque on the end effector, respectively. Parameter S is the time interval of the control system. The compliance-control mode was quite effective for performing the capture tasks.

The antenna-assembling mechanism also contains the mechanical compliance system. This system enables easy and reliable assembly using the robotic arm, which alone is low cost, less accurate, and unable to support compliance mode. The system is effective for following very fast and unexpected motions, whereas software compliance, such as the compliance control of ETS-VII, cannot follow motions much faster than the control cycle of the on-board controller, whose calculation ability is limited. If the compliance control is effective, the maximum speed of the robotic arm is 2 mm/s. However, with software compliance it is possible to change the compliance parameters, whereas the mechanical compliance system must be tuned for to the task beforehand. Two compliance-control parameters ("Flex" and "Hard") are available for each axis of the robotic arm.

We conducted an experiment to evaluate assembly using the compliance-control mode and confirmed that effective compliance parameters were generated for the antenna-assembly process. This experiment is important for understanding the detailed assembly dynamics of the antenna-assembling mechanism.

In all cases, harmful, unstable motion was not observed, so the mechanical compliance does not conflict with the software compliance. However, one of the assembly status indicators did not change regularly after assembly using the flex-compliance mode. The end-effector position was shifted during assembly, whereas the shift of the attitude was negligible. The X axis is the axis along the length of the AAM, the y axis is the axis along the width of the AAM, and the z axis is the approach axis. Rotation around the z, y, and x axes indicates, respectively, roll, pitch, and yaw. To confirm these results, we evaluated using the flex-compliance mode along the XYZ axis and the same mode only along the Z axis. The assembly status did not change regularly after the assembly along the XYZ axis, whereas it did after the assembly along the Z axis. This suggests that the compliance parameter should be "hard" for the antenna-assembling mechanism.

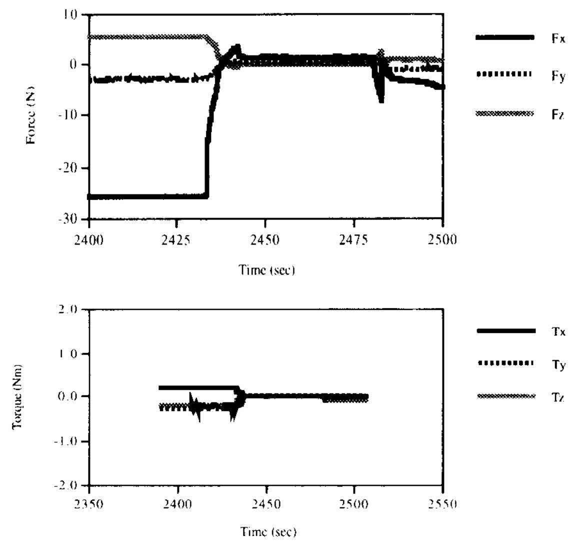

Fig. 4: Force and Torque at the End-Effector during Assembling- Disassembling Process

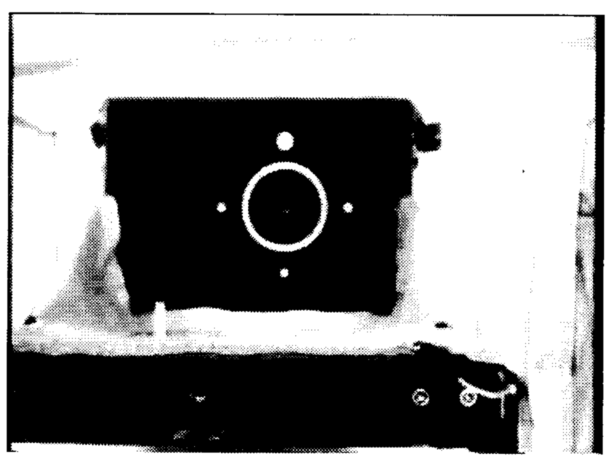

Fig. 5: Downlink Image of Target Mark through Hand Camera

3.2 Measurement of Combinable Area

To check the mechanical mechanism for adjusting the combining position, the combining position was deliberately shifted from the proper one. The AAM was designed to adjust the combining position even when it is out of position by up to 6 mm in any direction and by an altitude of up to 2 degrees in any direction. Considering the accuracy of the robotic arm for positioning, ten cases, namely x and y axis shifts of Å}5 mm and roll, pitch and yaw shifts of Å} 1 degree, were checked. In all cases, the mechanical compliance system adjusted the combining position effectively, and the assembly was performed successfully and reliably. The force needed for assembly never exceeded 8 N. These experiments confirmed the abilities of the AAM's mechanical adjusting mechanism.

3.3 Check of Auto-Positioning Using Image Processing

To perform fully automatic assembly, the teleoperation system for the antenna assembly experiment has an auto-calibration function that uses the downlinked image of the "Target Mark" on the AAM-FP (shown in Fig. 1). This image is taken by the camera mounted on the robot hand, so it is affected by the position and attitude of the robotic arm. The teleoperation system calibrates the robotic arm position from the downlinked image and automatically adjusts the position of the arm.

As the first step in testing fully automatic assembly, we checked the auto-positioning function of the teleoperation system at five positions. The calibration error in the x-y direction was 2.26 mm in the worst case, which is much lower than the 5 mm required for fully automatic assembly; that in the z direction was 1.85 mm in the worst case, which is also much lower than the tolerance of 10 mm. Figure 5 shows a downlinked image of the "Target Mark" used for checking the auto-positioning function. These results suggest that the auto-positioning function of the teleoperation system worked well and is suitable for fully automatic assembly.

3.4 Checkout of Master-Slave Control

The CRL and NEC planed to perform experiments on advanced control of space robots using a master arm. [5]-[6] For the first evaluation of the master-slave control system, we checked the stability and effectiveness of the master-slave control system during simple operations. This is the first case in which master-slave control was utilized for space robots. Figure 6 illustrates how the operation works. The estimated bilateral control function was confirmed: the end-effector was successfully guided to the top of the cone. This guidance increases the operation efficiency. These results suggest that the master-slave control system is quite stable and effective.

3.5 Evaluation of Audio Feedback System using Eye Mark Recorder

To evaluate the effectiveness of the audio feedback system, the operator's viewpoints were recorded by using an eye-mark recorder during the capture task with and without audio feedback (Fig. 7). The time required to cap-

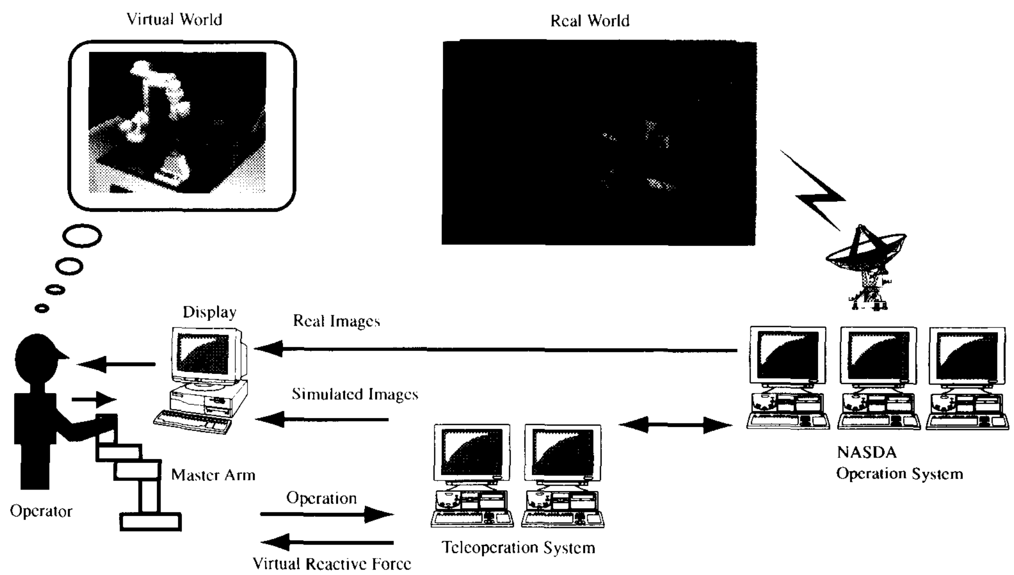

Fig. 6: Virtual Bilateral Control

ture the target when using audio feedback was shorter than when audio feedback was not used. When audio feedback was used, the operators paid attention to various information inputs, including the downlinked images, while without audio feedback, the operators primarily concentrated on watching the telemetry. These results suggest that the audio feedback system is quite effective because it reduces the need to concentrate on the telemetry data. We are now continuing our experiments and analyzing the use of the audio feedback system and the eye-mark recorder.

4. CONCLUSION

We have described the basic antenna-assembly experiments we conducted using ETS-VII and presented some initial results. The latch mechanism of the antenna-assembling mechanism, the mechanical compliance system, and the visual guidance system were all successfully checked out and their effectiveness was confirmed. The antenna-assembling mechanism was successfully assembled when there was displacement of up to 5 mm in position and 1 degree in attitude by using its own adjustment mechanism. We plan to perform further experiments on teleoperation at later stages of the satellite's mission.

References

[1] T. Iida, K. Okamoto, Y. Ohkami, S. Kibe, H. Koshishi, M. Naka, and H. Yamamoto, "A Space Station Experiment on Large Antenna Assembly and Measurement", Acta. Astronautica, 12, pp. 335-344 (1985).

[2] Y. Suzuki, S. Kimura, T. Takahashi, K. Nakamura, and H. Morikawa, "Antenna-Assembling Mechanism Test on ETS-VII", In Proceedings of Third International Symposium on Artificial Intelligence, Robotics and Automation for Space, Pasadena, U.S.A., pp. 279-284 (1994).

[3] T. Okuyama, S. Kimura, and M. Takahashi, "Teleoperation System for Experiment on Antenna-Assembling Mechanism on ETS-VII", In Proceedings of Fourth International Symposium on Artificial Intelligence, Robotics and Automation for Space, Tokyo, Japan., pp. 69-72 (1997).

[4] S. Kimura, T. Okuyama, and H. Morikawa, "Teleoperation of Space Robots for Antenna Assembling Experiment on ETS-VII", Space Ops 98, 2a007 (1998).

[5] H. Morikawa and N. Takanashi, "Ground Experiment System for Space Robots Based on Predictive Bilateral Control", IEEE Int. Conf. on Robotics & Automation, pp. 64-69 (1996). Å@Å@

[6] N. Takanashi et al., "A High-sample-rate robot control system using a DSP based numerical calculation engine", IEEE Int. Conf. on Robotics & Automation, pp. 1168-1173 (1989).

S. Kimura, T. Okuyama, Y. Yamana, Y. Nagai, and H. Morikawa, "Teleoperation System for Antenna Assembly by Space Robots", Telemanipulator and Telepresence Technologies V, ed. M. R. Stein, SPIE, 14-23 (1998).

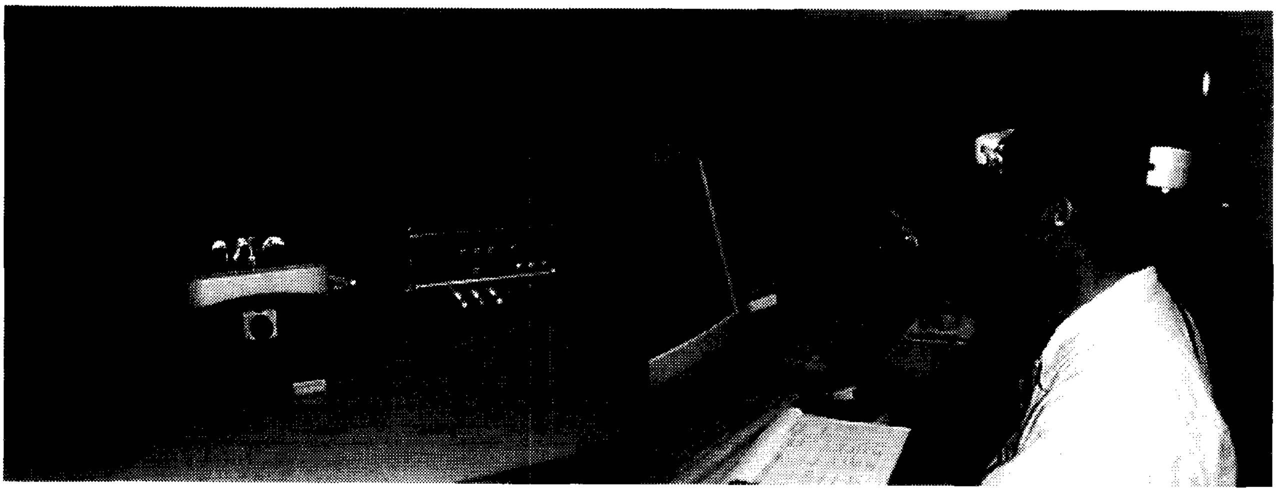

Fig. 7: Evaluation of the Teleoperation System Using Eye Mark Recorder