Performance Evaluation of Advanced Robotic Hand System in Space Experiment

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Abstract

This paper presents the overview of a space test of the world's first precise extravehicular telerobotic system named ARH (the Advanced Robotic Hand system). It was boarded on Engineering Testing Satellite VII (ETS-VII) developed by NASDA, and was launched into low-earth orbit in November 1997. MITI/ETL has been conducting the researches on a precise telerobotic system. This time MITI along with the Institute for Unmanned Space Experiment Free Flyer (USEF) have developed the ARH system and carried out the space experiment on ETS-VII to prepare the robot technologies for efficient industrial utilization of space in the near future.

The objectives of the ARH space experiments are to evaluate the capability of the semidexterous robot hand for executing precise and delicate tasks and to validate the related technologies implemented in the system, which are multi-sensory, multi-DOF, and multi-finger control. Almost all of the experiments were carried out successfully and the results of them were found to be the expected ones.

1. Introduction

It has been a while since we human being started using a word like a space age. Space technology has been surprisingly developed and they say that it must not be just a dream for a person in the street to go for a space trip. International Space Station program is now ongoing and other such kind of space program which will have to be constructed or maintained on orbit will become accomplished in the near future. Such construction or maintenance so far has been achieved mainly as the U.S. space shuttle mission using space robot controlled by the clew on the space shuttle. Even the clew himself or herself sometimes has taken an extravehicular actions. It could be said that the extravehicular activities by a person are not only very dangerous but also expensive although it is supposed to be the most precise working action to take on orbit. Meanwhile the space robot so far had no ability to handle rather small parts such as sample cartridges, bolts or electric connectors. If we human beings succeeded in developing such high performance space robot as an unmanned precise extravehicular telerobotic system, which is durable enough to be able to work for long time, then cost, time, and also jeopardy for the clew would be saved.

This kind of space robot should have an ability of precise work, for example, of carrying an instrument to an unexpected place or of replacing an abnormal instrument with new one handling some electric connectors and/or bolts. It would also be required some skills to handle a flexible object like wire, solar cell sheet, and even a floating object would be required to be grasped. Moreover, considering the insufficient tele-operability caused by the communication time lag, it should have adequate autonomy using several sensors as well as adequate performance of the ground system. The ARH system[1] was designed and fabricated to evaluate the capability of such kind of possible robot hand for precise work and to validate the related technologies we have been studied so far. In 1993, German program called ROTEX[2] had succeeded in performing an onboard precise space robot experiment. The major differences between our ARH experiment and the ROTEX's are that the ARH is expected to i)be an extravehicular space robot, ii)work for long time up to one and a half years, iii)be an space robot of which the end effector or the hand can be attachable to the different kind of space robot arm on orbit.

2. System Description

The ARH system consists of a mini arm of around 0.7m, a hand which is able to be attached/detached to/from the mini arm, a task board, a control computer, a power unit, a task panel, and a ground operation system (see figure 1 and 2).

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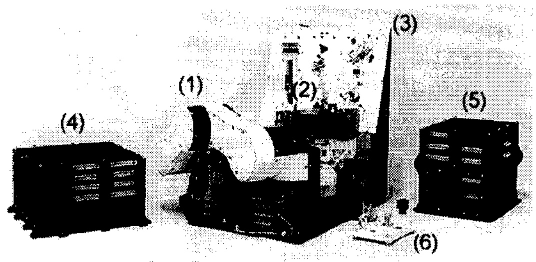


(1)mini arm, (2)hand, (3)task board, (4)control computer, (5)power unit, (6)task panel
Figure 1: ARH Onboard Components

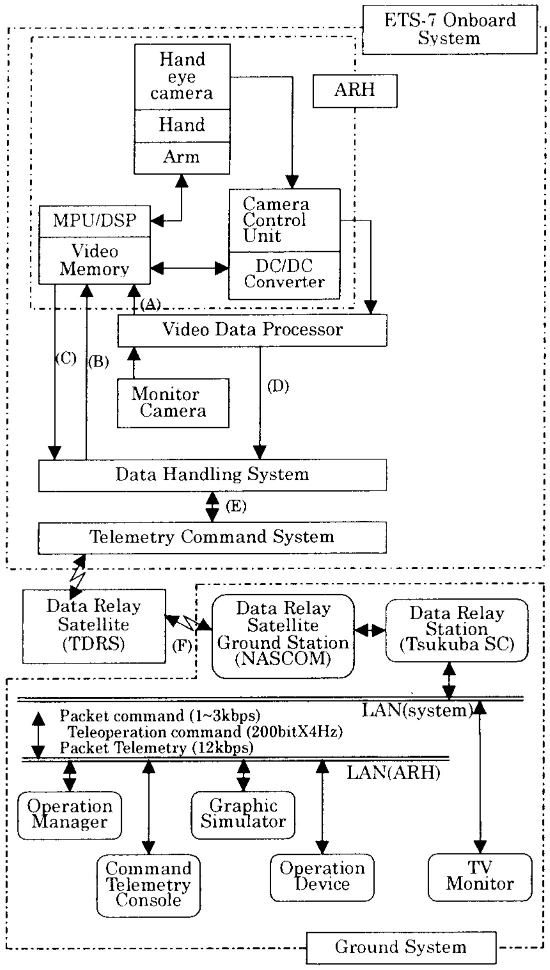
Figure 2:Ground System Configuration

Onboard experiment has been carried out in both configurations of i)stand-alone mode where the hand is attached to the ARH's mini arm and ii)long-arm-connected mode where the hand is connected to the NASDA's long arm called ERA[3]. The former mode was mainly focused on obtaining some expertise to control the precise semi-autonomous tele-robotics system. And the latter one was focused on the feasibility study of attaching the highly precise ARH's hand to the ERA in an attempt to give the ability of precise work to it, which has rather coarse positioning accuracy compared to the ARH's one.

The ground system was set up at NASDA Tsukuba Space Center and has controlled all of the ARH's tasks. The communication link between the ARH onboard system and its ground system has been established using the geo-stationary data relay satellite via the NASA Goddard Space Flight Center (see figure 3). The data rate of the uplink is around 4kbps and that of the downlink is around 1.5Mbps for which the video signal is dominant. The overall communication time lag is 5-6 seconds including uplink and downlink.

2.1. Mini Arm

The mini arm is a 5-degree-of-freedom



(A)Hand eye camera image data 4f/s
(B)Packet command
(C)Packet telemetry
(D)Compressed video data 1.2Mbps
(E)Packet Data
(F)Up-link 4kbps / Down-link 1.5Mbps

Figure 3: System Block Diagram

(5-DOF, R-P-P-P-R) space robot of around 0.7m and its positioning accuracy is around 1mm, allowing it to perform precise space experiments. It also has a 6-DOF force torque sensor to achieve delicate tasks. One of the distinctive features is that the hand could be attached/detached to/from this mini arm so that the hand could be attached to another 2m long arm or ERA of which the positioning accuracy is around 10mm. This reconfiguration was carried out as one of the ARH's extended experiment – long arm connected mode- described later (see chapter 3).

2.2. Hand

As is shown in figure 4, the hand[4], which is the key component of the ARH system, has three fingers and four kinds of sensors for precise works. It has a hand-eye CCD camera and three LASER range finders as non-contact sensor for determination of working positions, and a wrist compliance sensor, and grip force sensors as contact sensor for fine positioning and delicate force control in gripping, attaching, and detaching objects. Using this multi-sensory hand, ARH system can work as semi-autonomous robotic system as well as telerobotic system.

2.3. Task Board

As is shown in figure 5, the task board is an experiment panel for the evaluation of the

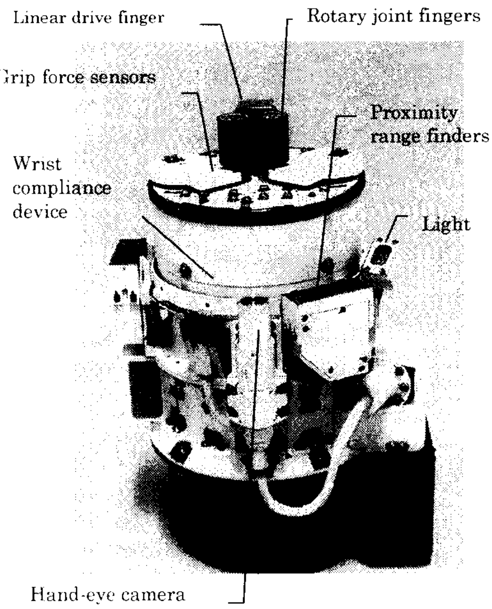


Figure 4: Hand configuration

performance of the system. This panel has a connector with an LED and its switch to check if the connector insertion is completed properly. It also has a bolt, a floating object, a solar cell sheet, a thermal blanket, and a wire to be handled with the hand.

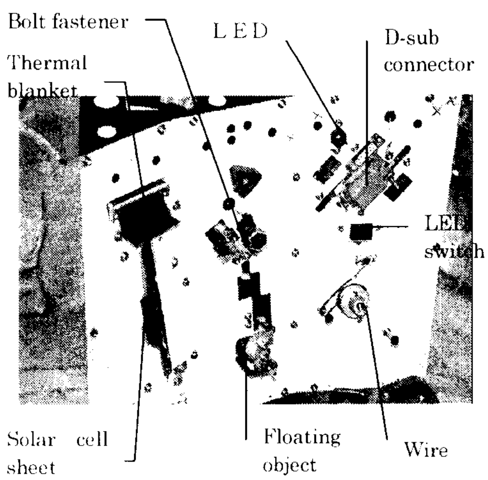


Figure 5: Task Board Configuration

2.4. Control Computer and Software

The control computer consists of 80386+80387 as the MPU with memory of 128kB and 256kB for ROM and RAM respectively, and a DSP for controlling the mini arm. The software(5) of each of the experiments such as a bolt or connector mate/demate experiment is to be installed separately on the multi-task operating system using application program interface or API, where these software on the RAM is able to be rewritten by the tele-command so that the system could be flexible and be executed with limited hardware resources. This software structure can also make the system serve as a flying test bed for a space robot, where users can perform some experiments using their own logic.

2.5. Task Panel on Target Satellite

The task panel is an experiment panel boarded on the target satellite of ETS-VII, which is used during the long-arm-connected mode. It consists of an electric connector and a bolt, which are handled with the hand connected to the ERA. Figure 6 is the view of the task panel through the CCD camera of the ERA.

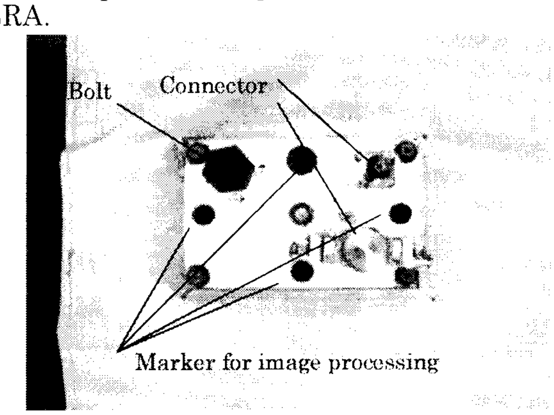


Figure 6: Task Panel (onboard)

2.6. Ground System

As was shown in the figure 2 and 3, the ground system consists of an operation manager, a telemetry and command processor, and a graphical simulator. In order to watch the onboard status, we constructed real-time images of the robot on the display with computer graphics using the telemetry data. The motion prediction images are also visualized on the same display using the tele-command data. Moreover, the onboard sensor status are visualized so that the operator can get almost all the onboard status with just a glimpse of the computer display. This computer-generated camera, of which we call a "virtual-hyper camera[6]", provides much more important information than a real TV camera, which also requires much more data to transfer.

Regarding the master device to operate the robot, we chose a mouse-like device as shown in the figure 7, where our former study[7] with respect to the master device for a space robot concluded that the best one was the mouse type on the grounds that the space robot does not necessarily move in 3 dimension at the same time. Other type of master device has some problem of operability from the point of view of operator's fatigue.

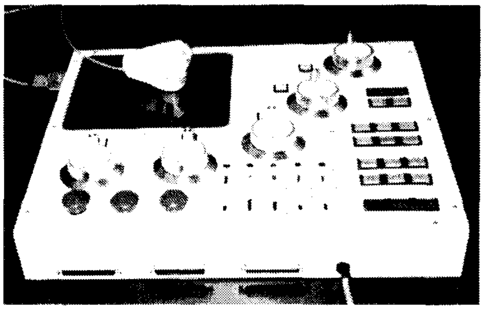


Figure 7: Mouse Master Device

3. Technologies to Evaluate

All the experiments have been carried out in two configurations as is shown in Table 1: an ARH stand-alone configuration and a long-arm-connected configuration as was described in chapter 2. And also there are three operation modes to carry out these experiments: autonomous operation mode, tele-operation mode, and fusion mode.

In this table, the technologies to evaluate are also shown. In order to achieve these experiments, total system performances are required, not only the positioning accuracy of the mini arm or the fingers, but also the image processing performance, resolution and stability of all the sensors including the LASER range finders, force torque sensors, and so on.

3.1. Stand-alone mode

Considering the utilization of a semi-autonomous and tele-operable space robot in the near future, the expertise of handling an electric connector, bolt fastener, or even a floating object has to be obtained through the experiments as described in the introduction. The connector installed on the task board as a handling object is just the same D-sub connector as we use for the space components. It allows only around +/-0.5mm as the positioning error to mate. So sub-millimeter level control is requisite to perform this task. Without any aid, it would be very difficult to achieve this experiment considering the positioning accuracy of the space robot. So the precise positioning performance with the aid of the image processing technology should be evaluated. Also the grip force control technology should be evaluated in order to mate the electric connector. With respect to the bolt fastener mate/demate experiment, it would be very difficult to detect whether the fastener is in mesh. So the screw motion control and re-grasping technology including wrist and grip force control should be verified. Regarding the capturing of a small floating object under the zero gravity environments, the 3D-position measurement and capturing technology using the LASER range finder should be verified. Furthermore, in order to handle a flexible object like a wire, which is difficult to be handled autonomously because of its every-changing shape, the effective teleoperation with the aid of the motion prediction technologies is required.

In the experiment called working in eclipse, the feasibility of carrying out the tasks

Table 1: Space experiment and Key Tech.

Mode & Task	Technologies to Evaluate
Stand-alone mode	
Connector mate/demate (A,T)	Precise positioning, precise part insertion and grip force control
Bolt fastener mate/demate (A,F)	Screw motion control under force monitoring and re-grasping.
Floating object capture (A,T)	3D-position measurement and capturing a floating object in 0g.
Solar cell sheet handling for power generation (A)	Handling technology of flexible sheet
Wire handling (T)	Handling technology of flexible wire and teleoperation by virtual operator method
Working in eclipse (A)	Effectiveness of virtual-hyper camera
Long-arm-connected mode	
Connector mate/demate	Error compensation of long arm
Sample return	Work environment measurement and error compensation of long arm

The uppercase letter A, T, and F following the description of the "mode & task" stands for "autonomous", "tele", and "fusion" operation mode respectively, which means the operation mode to be applied.

under the eclipse with the aid of an LED illuminator installed on the side of the hand should be verified. This is on the grounds that the workable time of the space robot would be seriously limited if it were not able to work in eclipse as it is now.

3.2. Long-arm-connected mode

By handling the connector and bolt installed on the task panel(see section 2.5) using the hand connected to the ERA, the feasibility of attaching the highly precise hand to the rather not so precise space robot should be verified. Rather larger-scale space robot would not have enough positioning precision to handle an electric connector or a bolt.

4. Results

Several experiments were carried out over five times of experiment windows, which has been planned to accomplish over one and a half years. Each window consists of around three-five consecutive days.

4.1. Reconfiguration on orbit

First critical event, which was carried out in March 1998, was the reconfiguration of the robot system on orbit including launch lock relief and hand attaching sequence because the mini arm and the hand were locked separately by mechanical cramps when they were launched (see figure 8).

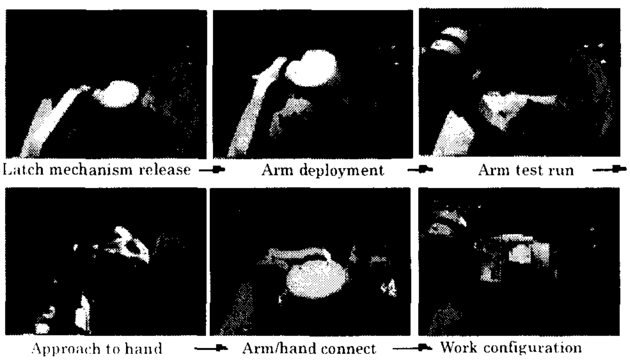


Figure 8: Reconfiguration

With respect to the launch lock relief sequence, we feared the cold welding as well as the hot welding, which might be caused by the evacuated thermal cyclic environment and mechanical vibration respectively. Metallic contact surface between these cramp mechanisms and both of the mini arm and the hand were processed by solid state lubricant for the measures. The telemetry data of the wrist force and torque sensor for the experiments showed rather lower level of maximum 18N and 0.9Nm compared to the ground test result. This means there was no welding on orbit.

With respect to the subsequent hand attach test, the major concern was the position error of the hand attaching location and orientation because the exact position in the zero gravity field was not able to be measured on the ground. By adjusting these errors using force feedback control technology, this task was carried out with no trouble. Figure 9 shows the wrist sensor and the arm position. The maximum load to the arm was around 15N. The axial force F_z reached 17N when the interface of the hand contacted that of the arm. These results were found to be lower level compared to the ground test. Initial checkouts for all mechanisms including all the sensors were carried out after the hand was attached.

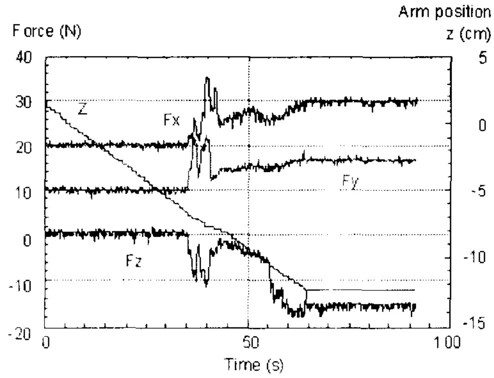


Figure 9: Wrist Force in Hand Connection

Through these system checkouts, we could confirm that the mini arm and the hand system could work well in space. Also we could found that the noise level of all of the sensors were low compared to the ground test.

4.2. Electric Connector Mate/Demate

Electric connector mate/demate experiment was carried out as the first major task for this system in July 1998 on the second window. This experiment was carried out in both modes of autonomous operation and tele-operation.

First, under the autonomous operation mode, using the LASER range finder measuring three points on the task board, the attitude of the hand was set vertical to the task board. Then the local coordinates of the task board were created using the hand eye CCD camera measuring the several circular markers on the task board. This approach, we think, will be very efficient under the condition that the absolute position and orientation of the parts like connector are unknown, where the only thing we should know is the local position and orientation. The positioning accuracy we could obtain by using this technology was around +/-1mm. This accuracy seems enough for the other handling objects, but the electric connector is an exception, which requires at least 0.5mm accuracy.

As the next step, we took an image of the receptacle of the connector itself using the hand eye camera (see figure 10) and processed the image of the pinholes of the connector (see figure 11) in order to determine the precise location and orientation of the connector.

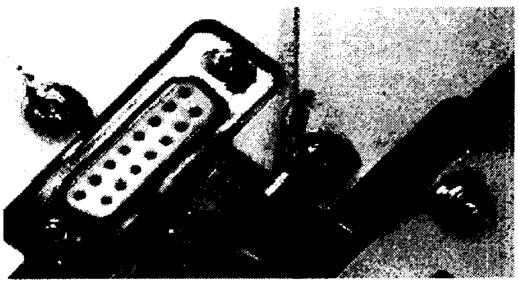


Figure 10: Connector image picture

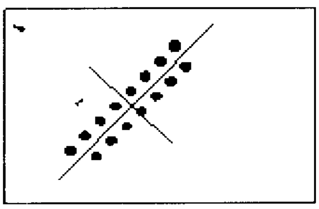


Figure 11: Processed image

By using this technology we could obtain the positioning accuracy of around +/-0.25mm. After measuring the accurate position of the receptacle, the connector was inserted to it using the passively controlled compliance mechanism, which would compensate the residual positioning error. Figure 12 shows the wrist force sensor when the connector was inserted.

Through this experiment, we could confirm the electrical connector could be handled with the multi-sensory space robot autonomously. And we could confirm the effectiveness of this image processing technology, although we also found this needs more considerations. We had some trouble to adjust the shutter speed of the camera to the every-changing lighting condition for obtaining the best image. This might be caused by the lack of the pixel numbers of the pinholes of the connector or by the effect that the sunlight incidents directly into the pinholes, which hinder sampling the pinholes.

The experiment under the tele-operation mode was carried out on the following day. The simulator, displaying the attitude and position of the mini arm as well as the fingers based on the command of 4Hz and the telemetry of 8Hz, was found to make the tele-operation easier, although the communication time lag of around 5-6 seconds was expected to hinder the timely operation. We could demate the electric connector successfully, but the connector mate experiment by tele-operation was unsuccessful.

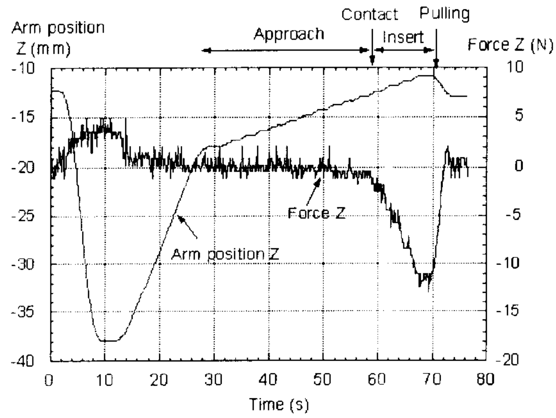


Figure 12: Connector Insertion

By analyzing the experiment results, we found that the real position of the connector was off to the side of around 4mm compared to the position that the graphical simulator indicated. We estimate that this may be caused by the several following reasons. One is that we omitted such models as the passively controlled wrist compliance mechanism from the simulator. Second is that the CPU load of the graphical simulator on which the operator could only depend became high during the operation, and the commanding interval kept changing, which made the operability worse. Third is that the force torque sensor output with some bias noise, which operator could not detect the position where the insertion was completed. We think this might be a lesson to learn about how to carry out a simulator-based tele-operation for a space robot.

4.3. Bolt Fastener Mate/Demate

Bolt fastener mate/demate experiment was carried out on the third window in October 1998. In order to mate the bolt, the axial center of the rotational axis of the mini arm and that of the bolt should be coincident. Also the status whether the bolt is in mesh properly should be detected. This experiment was carried out in fusion operation mode, where either the autonomous mode or the tele-operation mode was applied according to the circumstances.

First, the local coordinates were created as the same procedure as described in section 4.2 to know the location and orientation of the bolt, which was installed into the lower receptacle. Then the bolt head was grasped. The relative location of the bolt against the hand was detected by knowing the position of each finger. Using these data, the axial center of the mini arm was adjusted to the bolt autonomously. Then the bolt was screwed to the loosening direction to the movable limit of the arm of 180degree. After that the bolt was pulled to the axial direction in order to confirm the bolt was demated. By iterating this procedure, the bolt was demated properly.

After inserting the tip of the bolt to the another upper receptacle, the bolt was screwed to the tightening direction. Then the bolt was pulled to the axial direction as the same way in demating in order to check if the bolt was in mesh. By that time, the experiment was carried out in autonomous operation mode. After that time, we switched the operation mode to fusion mode in order to confirm the effectiveness of it, which compensates the technologies that are insufficient in the tele-operation mode. In this operation mode, the local autonomy of the onboard system, for example the grip force control, was used.

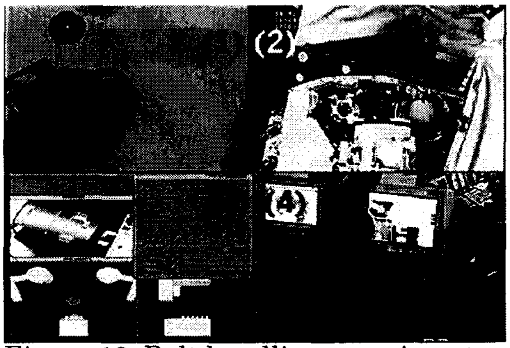


Figure 13: Bolt handling experiment

(1)Image through hand eye camera. (2)Image through camera on ERA. (3)Graphical simulator. (4)Operation scene.

The bolt was pulled to the axial direction with the force of around 7N. Then the bolt was screwed to the loosing direction monitoring the wrist force in order to detect the meshed angle, which was found to be 27 degree. Released and inserted to the lower receptacle again, the bolt was screwed to the fastening direction. And the meshed angle was checked, which was found to be more than 30 degree. Then the bolt was fastened properly. Figure 13 shows a scene of this experiment.

On the next 4^{th} experiment window, the bolt handling experiment was carried out using the advanced function(9) of the graphical simulator, which is expected to improve the tele-operability. In this experiment, the simulated 3-D computer graphic was overlaid on the real video image of the hand eye camera (see figure 14). And the action for the onboard system to take was indicated with the mouse of the computer using a drag&drop-like operation style, where we call it a tele-programming operation. This is just the same way as the mechanical engineers design the hardware using the CAD system on their personal computer.

Through this experiment, we could confirm that the bolt fastener could be handled with our technology in both ways of autonomous operation and tele-operation. Also we could confirm the effectiveness of the advanced function of the graphical simulator.

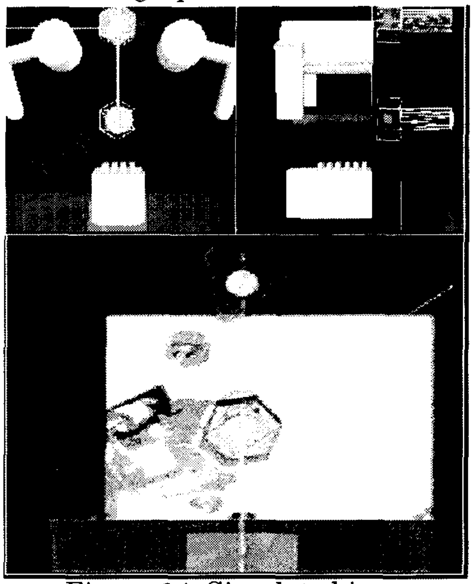


Figure 14: Simulated image overlaid on the real video image

4.4. Floating Object Capture

The floating object is an aluminum sphere of around 30mm installed onto the task board as shown in figure 5. This experiment was carried out as the tele-programming experiment.

After released, the floating object was supposed to be searched with the LASER range finder scanning the appropriate region where the floating object was expected to be. After detecting the approximate position of the floating object, which could be calculated from the distance measured with the LASER range finder and the attitude of the arm, the floating object was supposed to be captured. Actually the experiment was aborted and postponed because we have had a trouble after grasping it. The grip force sensors indicated unexpected value when it was grasped. We have been analyzing the experiment data and we suppose that the floating object was adhered to the launch-lock mechanism. However, through this teleoperation experiment, we think we could confirm the effectiveness of the tele-programming operation.

4.5. Working in Eclipse

Under the eclipse environment, the only thing we could depend is the virtual-hyper camera or the graphical simulator because all the video monitors would not work for lack of the sunlight. Turning on the LED installed on the side of the hand, we carried out the same image processing procedure of the connector experiment as described in section 4.1. As the result, the image obtained through the hand eye camera was dark as we expected, but was enough to process by CPU (see figure 15). Every step of the procedure was carried out with no trouble and we could confirm that the LED of around 1W is enough to get the images for the image processing. Also the effectiveness of tele-operation using the virtual-hyper camera was confirmed. Furthermore, we could find that the lightning condition was rather better than that in the sun side of the Earth because there is no more every changing situation in eclipse.

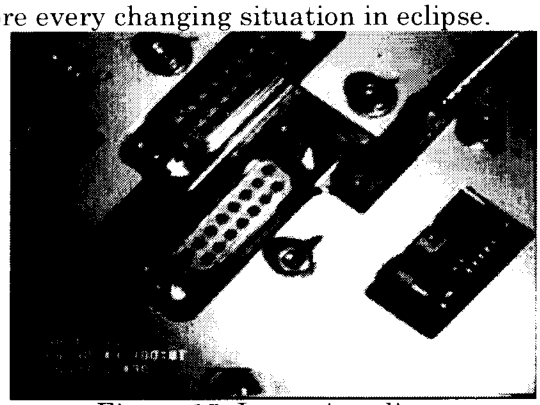


Figure 15: Image in eclipse

4.6. Summary of Other Experiments

The Solar cell sheet handling experiment was carried out by the multisensory autonomous control, and the LED illumination powered by the solar cell was confirmed through the hand-eye camera. The wire handling experiment was achieved by teleoperation from the ground. The details are presented in the accompanied paper[10]. In the long-arm connected mode, the connection of the hand to the long arm ERA has been successfully carried out in May 1999, and precise in-orbit servicing to the task panel on the target satellite has been performed.

5. Conclusion

We have carried out several in-orbit servicing experiments in order to evaluate the capability of the semidexterous robot hand for executing precise and delicate tasks as well as to validate the related telerobotic technologies implemented in the system.

Through these experiments, we could confirm that the three-finger multisensory hand of this robot system is valid enough to carry out the precise tasks autonomously in orbit.

We could also confirm that the teleoperability of this system is efficient enough to carry out in-orbit precise works with the aid of the local autonomy of the onboard system as well as the computer-graphics-based telerobotic function of the ground system in spite of the insufficient communication capacity, the unavoidable communication time lag, and unsatisfactory information of the video images.

More detailed information about the ARH including the results of the space experiments is on the Internet at http://www.etl.go.jp/~5822/ARH/ARHEng.

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