GENERALIZED VISUAL AID FOR DIRECT TELEOPERATION APPLIED TO ETS-7 TRUSS MANIPULATION EXPERIMENT

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ABSTRACT

This paper reports the latest results of a newly developed visual aid system for direct teleoperation applied to the ETS-7 truss deployment experiment. This aid system does not depend on a designed model of the workplace. It introduces the "predictive force" to calculate the appropriate joystick input, and displays it to the operator in the joystick coordinate system to enable the operator easily follow the direction. This "predictive force method" is extended to automatic programming to make an efficient teleoperation system by combining the direct teleoperation and the program control.

1. INTRODUCTION

For the future space activities like International Space Station, teleoperation is considered one of the most needed technologies to reduce and supplement on-board operation helping the astronauts. And the tasks which teleoperation would substitute are expected to increase in quantity and become more complex.

If there is a precise designed model of workplace on the ground, the program control can perform better than the direct teleoperation by human operator. Still, we need a practical system for direct teleoperation, which effectively supports the operator to conduct the whole operation. This is partly because there is fairly big modeling error in space systems and partly because the program control can not handle unexpected situations.

Thus, we first developed and tested a new visual aid system for direct teleoperation to calculate and display the appropriate input to the operator without using a designed model, by introducing "predictive force".

On the other hand, if an aid system is designed based on the analytical algorithm, there seems to be no clear advantage in direct teleoperation. This is because the program control can do the same or even more precise work, if the next input is determined by calculation. The error of the program control is usually far less than that of the unstable human input. So next, we expanded the algorithm of the predictive force method into automatic programming to realize program control without a designed model.

The direct teleoperation is useful in coping with unexpected situations or making small adjustment during the operation, while the program control excels in precisely following an algorithm. It seems that the best teleoperation system is a combination of the direct teleoperation and the program control. We think that a teleoperation system first should be equipped with an effective aid system for direct teleoperation, and next, the analytically determined operation should be replaced with program control.

The input device for direct teleoperation is also important. Direct input devices like joystick or master-arm are generally considered flexible and useful in teleoperation system compared with program control. And we adopted joystick as an input device for our truss manipulation experiment on the Engineering Test Satellite 7 (ETS-7). However, it seems that the direct teleoperation using those devices is not so capable without a proper aid system. This is especially true for dexterous operations and the main reason is the difficulty of making complex input. It is better to show the operator the input direction directly connected to the input device.

From the next section, we describe the newly developed aid system, its extension to program control, and their combined system, based on the results of the truss manipulation experiment on ETS-7.

2. TRUSS EXPERIMENT ON ETS-7

ETS-7 (Engineering Test Satellite 7), launched by NASDA Nov. 28, 1997 in Japan, had been developed to demonstrate two major missions, the rendezvous docking and the space robotics (Fig. 1). For the space robotics, it is the world first robotic-arm teleoperation experiment satellite.

NAL have participated the robot experiment along with other three national institutes. The basic robot systems of the satellite and the ground facilities, such as the arm, vision, communication, and the controller, had been developed by NASDA. NAL have developed our own experiment apparatus, TSE (Truss Structure Experiment apparatus), for the satellite and our own ground facilities related to tele-robotic research.

The ETS-7's teleoperation has two modes, the program control and the direct teleoperation control. We have mainly used the direct teleoperation control where the arm tip motion is controlled at 4 Hz directly from NAL's teleoperation facility. For the arm tip force control, the soft or rigid compliance control or the active limp control is used from the final capturing process and all over the handling tasks to avoid excessive force from the arm.

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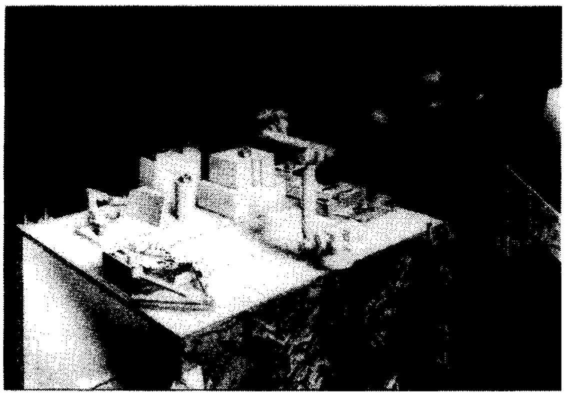
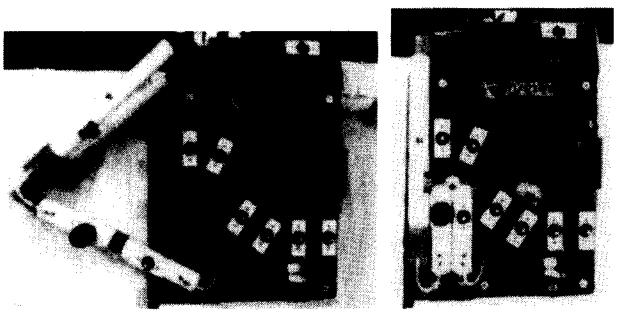


Fig. 1 ETS-7 (Engineering Test Satellite 7)

The TSE experiments have three components, the launch lock, the deployable truss, and the truss joint. The deployable truss (DT) has 10 degrees of freedom, and is a part of a triangle truss structure that is statically determinate and can be deployed and folded (Fig. 2).

The arm grapples the grapple fixture installed on DT and deploys it along a 3 dimensional spline curve under closed link arm control. The technical difficulty is to move the arm along the trajectory within suitable tip force and torque. The closed link movement along a strictly defined trajectory is the first operation for ETS-7.



a) b)

Fig. 2 TSE Deployable Truss
a) deployed position, b) stowed position

3. THE PROBLEM OF THE DIRECT TELEOPERATION OF DT

The trajectory of the deployable truss is a smooth three-dimensional spline curve, and the orientation of the grappling point also changes gradually along the trajectory. The handling of DT has shown that the direct teleoperation by joystick is almost useless without a proper operation aid. This is mainly because of the difficulty of tracing the complex deploying trajectory under communication time delay. It is so difficult to intuitively decide the next input that the operation tends to be a move-and-wait operation to confirm the result. Thus, the aid system should show the operator the proper input directions that are intuitively understandable.

In addition, the designed model of the trajectory is not reliable because of the modeling error caused by the launch impact or the thermal effect. Since the modeling error of the space structures can usually be more than several millimeters, the use of the designed model is not accurate. Furthermore, considering the efficiency of the future space activities where most of the tasks are not repetitive, the use of the precise designed model for all the tasks seems to be unrealistic, because it requires enormous database and a heavy load of calculation. To realize a practical aid system, it should not rely heavily on a designed model.

4. VISUAL AID SYSTEM USING PREDICTIVE FORCE METHOD

We have developed and tested a new visual aid system for deploying the truss which calculates the appropriate joystick input on-line and shows it to the operator by indicating the directions the joysticks should be moved to.

This method uses only the past trajectory and the present status, without using a designed model of the trajectory, and theoretically estimates the current force executed to the truss. We call this theoretical force as the predictive force. The basic idea is to move the current command point toward the tangential direction of the estimated trajectory calculated from the past data. The appropriate input to apply the needed force for deploying should be in parallel with the tangential direction of the current point (tangential input). When the current command position is not on the tangential line, another input is needed in the vertical direction of the trajectory to release excessive force (force-release input).

As these two input directions are converted into the joystick coordinate system and shown to the operator to follow the direction, the operator easily handles the complex operation without doing move-and-wait.

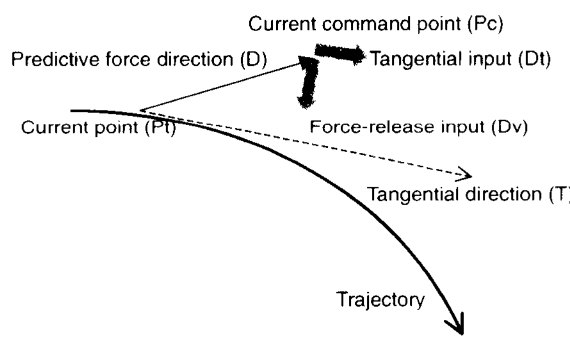


Fig.3 Algorithm of the Command Calculation using Predictive Force method

The algorithm of this aid system is shown in Fig. 3. In the below discussion, the bold symbols indicate vector value.

Fig. 3 shows the situation in the middle of the deployment. The robot is now at the current point **Pt**, and the current command point is **Pc**. The vector **D** (= **Pc-Pt**) is the difference between the command point and the current point, which theoretically corresponds to the direction of the force. If the parameter of the compliance control, fp (the force produced when $|D|=1$), is known, fp $\times$**D** (=**F**) is the theoretical force vector applied to the truss by the robot arm. We define this theoretical force as the predictive force.

Since the trajectory from past to present is known, the tangential vector of the current point, **T**, can be calculated by some numerical algorithm. By moving the command point **Pc** in order for **D** to overlap with **T**, the force vector **F** turns to the tangential direction **T** and executes only the deploying force.

In other words, the tangential component of **D**(**F**), which is in parallel with **T**, corresponds to the deploying force, and the orthogonal component of **D**(**F**) corresponds to the excessive force. The aid system displays to the operator the two directions, the tangential input **Dt** that increases the deploying force and the force-release input **Dv** that decreases the excessive force.

Pt, **Pc**, and **T** should use the latest value. It is possible to use the current command and the delayed telemetry together, if the time delay is relatively small. But, if the time delay is large, the time difference between **Pt** and **Pc**, and the calculation of **T** should be adjusted.

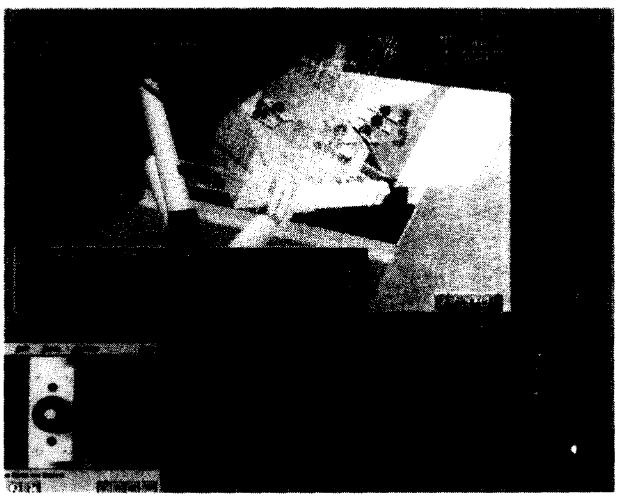


Fig. 4 Aid Display for TSE DT Operation

Fig. 4 shows the aid display we have used for ETS-7 truss deploying experiment. The upper part of the display shows the overview of the TSE and the lower part shows the operation information. The three windows in lower right shows the force-torque sensor value and the image processing result. The lower left window is the down link image of the on-board hand camera. The two windows in the lower center are the direct input aid for joystick. The left window corresponds to the translation input and the right window to rotation input.

Fig. 5 shows the detail of the input aid. The right window is the translation aid. The bold bar is to indicate the trajectory's tangential direction **Dt** and the box is to indicate the force-release direction **Dv**. The thin bar indicates the current operator input. The display matches the physical coordinate system of the input device, joystick in this case, in order for the operator to quickly follow the direction. The joystick axes are assumed to be vertical to the windows. If the bold bar points to the left, the operator is supposed to push the joystick to the left to execute deploying force. If the box is not around the window's center, the operator is supposed to push the joystick in the red box's direction to release excessive force. Thus, the ideal input should be the direction between the bold bar and the box like the one shown in Fig. 5. The vertical line in the right side indicates the third axis that is vertical to the window.

Fig. 5 Joystick Input Aid

The left window is for rotation input. The fan-shaped object shows the roll rotation allowance, because the DT's grapple fixture is not completely fixed and can rotate to latch or unlatch. If the two thin bars, one for current roll and the other for command roll, are within the fan, the excessive roll torque does not appear. The center box just shows the window center. The other box, almost in the center, shows the pitch and yaw input. They are calculated based on the difference between the current value and the command value, which corresponds to the theoretical torque. The pitch and yaw input is expected to reduce the difference.

The aid bars and boxes keep moving during the operation, and the operator follows them.

Fig. 6, 7 show the comparison of the telemetry trajectory and the command trajectory by the direct teleoperation using the visual aid system in stowing operation. Fig. 8 shows the translational force history. The coordinate system is shown in Fig. 9.

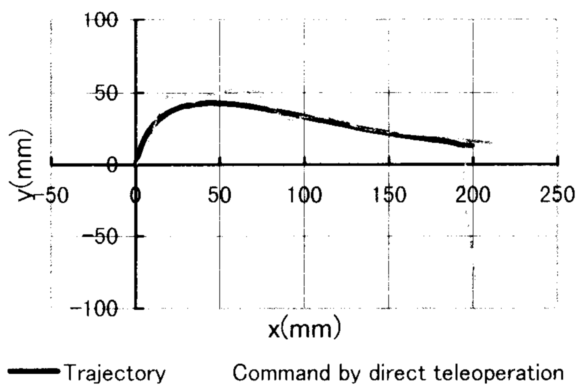


Fig. 6 Comparison of the Trajectory (x versus y)

The command trajectory shows that the visual aid system successfully helps the operator to trace the complex trajectory. Though the translational force is higher than that of the program control, the maximum force is around 15N and it is low enough for safe operation. The required operation time is about ten minutes. It is almost the same as the twelve minutes of program control, thus the move-and-wait operation was successfully avoided.

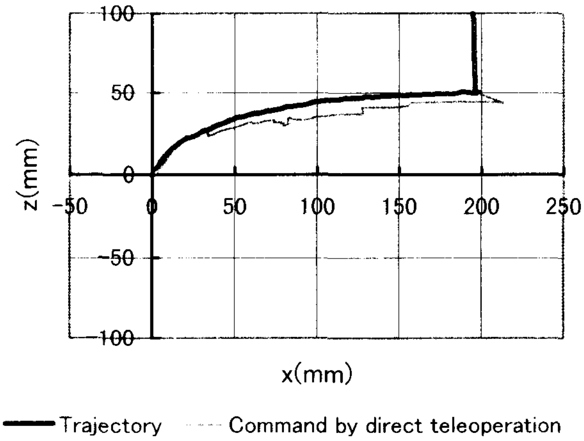


Fig. 7 Comparison of the Trajectory (x versus z)

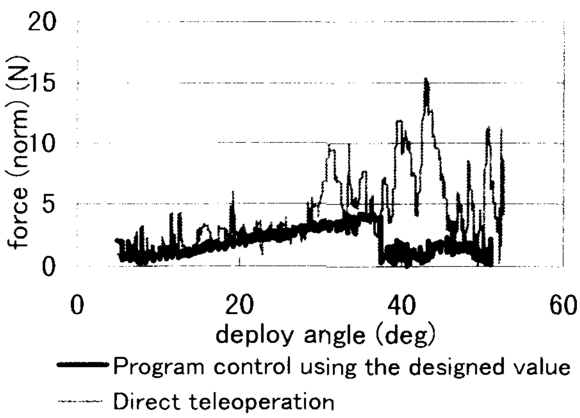


Fig.8 Comparison of the Translation Force

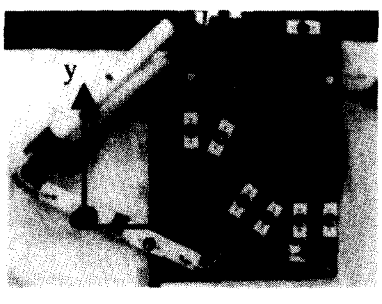


Fig.9 Coordinate System

5. PROGRAM CONTROL OF DT USING PREDICTIVE FORCE METHOD

In the above mentioned aid system, we introduced the idea of the predictive force. Here, we extend the idea into automatic programming. Fig.10 shows the algorithm. The same symbols in Fig.3 are used. By specifying the maximum allowable force value (|**Fd**|), which the real force should not exceed during the operation, the ideal command point (**Pd**), which theoretically applies the maximum force to the truss, can be determined uniquely in the tangential direction **T**. The targeted **D** is determined as **D'=Fd/fp**, and the targeted command point **Pd** is **Pd=Pt+D'=Pt+Fd/fp**. The move of the command from **Pc** to **Pd** usually takes more than one command, and thus **Pc** approaches **Pd** gradually with several commands. **Pd** is kept updated every cycle of commanding using the newly calculated tangential direction **T**. In this way, the force can be controlled under the specified value |**Fd**| during the whole operation.

This method performs better than the usual program control using a designed model of the trajectory, because it can avoid the excessive force due to modeling error.

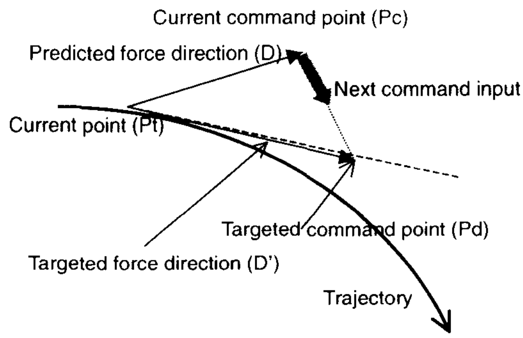


Fig. 10 Algorithm of the Program Control using Predictive Force Method

Fig. 11, 12 show the comparison of the command trajectory of deploying the truss by the program control using the predictive force method with the real trajectory. And Fig.13 shows the translation force history. In this case, the maximum force is specified as 10N and the tangential direction **T** is calculated by the least square method using the telemetry data from the past to the present. The coordinate system is shown in Fig.14.

The command trajectory by the program control shows that the predicted force method successfully generates the command trajectory without using the designed model. Though the command trajectory overshot the real trajectory due to the need of executing the deploying force and the communication time delay, the translational force is almost the same as the program control until the middle of the operation and even far lower in the last part of the deployment. This is because the predictive force method compensated the modeling error.

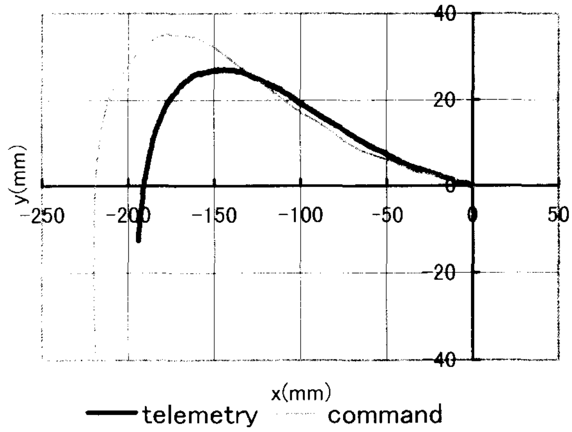


Fig. 11 Comparison of the Trajectory (x versus y)

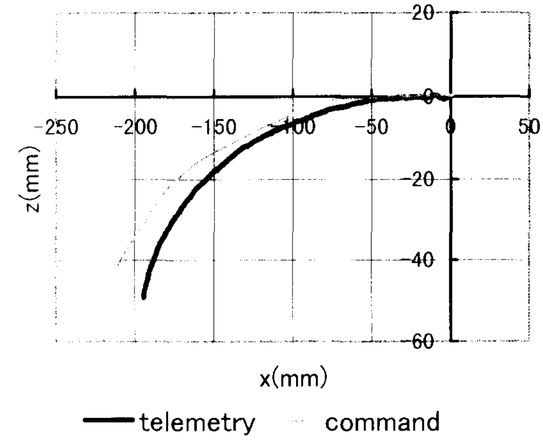


Fig. 12 Comparison of the Trajectory (x versus z)

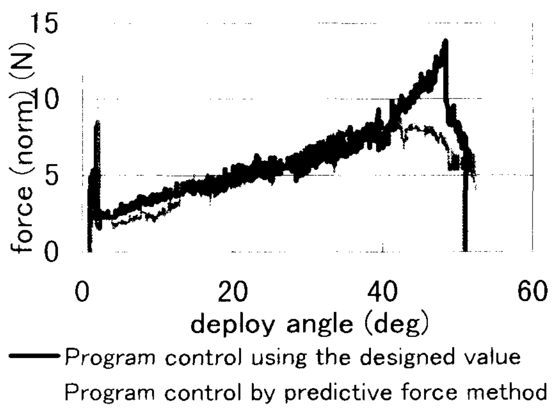


Fig. 13 Force History in Deployment

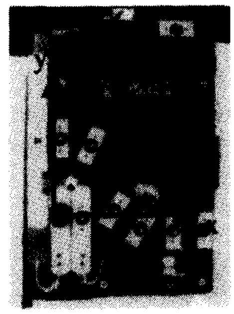


Fig. 14 Coordinate System

6. COMBINED SYSTEM

Direct teleoperation and program control have their own advantage and disadvantage. Direct teleoperation easily handles the discontinuous operation and the unexpected situations, and program control makes stable and precise input in continuous operation. So, we combined them to make an efficient teleoperation system.

Our DT requires two tasks in addition to the 3D spline curve movement. They are releasing the lock by rotating the fixture at the beginning of the stowing and surmounting the temporal fixture at the stowed position. And there is also start/end operation. These discontinuous operations are easy to be specifically programmed but difficult to be generalized. So, we assigned these discontinuous operations to direct teleoperation and the continuous deploying/stowing operation to program control.

Fig. 15 shows the command and information flow of the combined system. This system consists of the direct teleoperation aid system and the program control system both based on the predictive force method. There is an input switching which selects the input or makes overwritten input.

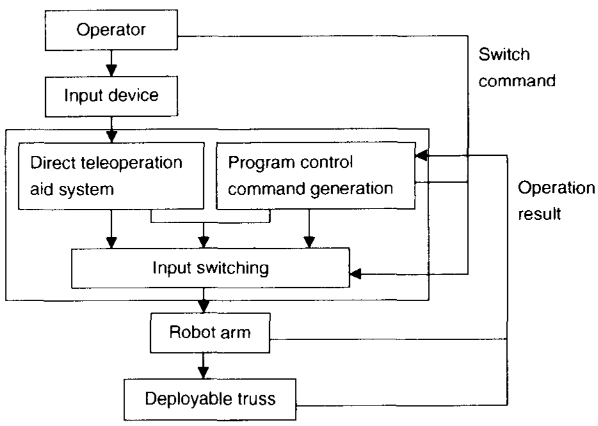


Fig. 15 Input and Information Flow of a Combined Teleoperation System

The operator starts the operation, and when the arm moves enough to start calculating the tangential direction, the operator stops joystick input and the program control takes over the deploying/stowing operation. During the operation, the operator just monitors it and overwrites the program command if necessary. At the end of the operation, the operator takes over the operation and does the final adjustment. In this way, flexible and continuous operation is realized without relying heavily on a designed model.

For ETS-7 truss deploying experiment, we usually use this combined system. It is very efficient to share the operation by the operator and the program control.

7. CONCLUSION

To realize a practical teleoperation system, we first developed a direct teleoperation aid system, which enables the operator to conduct a complex operation like truss deployment. This aid system is constructed without a designed model and based on the newly developed predictive force method which uses the theoretical force to determine the input for applying the deploying force or releasing the excessive force. The ETS-7 truss deploying experiment shows that the aid system successfully supported the operator to conduct the operation.

Then we extended the predictive force method into program control, which controls the force under the specified value during the operation. This program control makes more precise and stable input than the operator does. The calculation based on the predictive force method is simple and for general use.

Finally, we made a combined system of the direct teleoperation and the program control. In this combined system, the direct teleoperation handles the discontinuous operation like start/end operation or latch operation, and the program control handles the continuous deploying/stowing operation. This system showed great efficiency and has the possibility to be applied to general tasks, because it does not use a designed model and the calculation load is low.

To farther improve this system, the algorithm should take the communication time delay into account in estimating the tangential direction vector. We used the least square method for estimating the tangential direction vector. But, to take the communication time delay into account this method might be inappropriate.

In addition, the teleoperation system must be able to handle unexpected situation efficiently. Through our truss operation, we have the impression that joystick is not necessarily the most appropriate device for direct teleoperation where subtle adjustment or handling of unexpected situation is required. To operate precisely in those situations, we might need other input devices than joystick. The input method itself is also the future subject.

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