Experimental Study for Dual-Manipulator-Based Operation of Floating Massive Payload

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Abstract

A robot satellite with dual-manipulators is one of the choices to operate payload in orbit, for example, to capture or deorbit damaged satellites. We have constructed a ground experiment simulator system including two 7-degree-of-freedom (DOF) manipulators as a chaser satellite model and floating testbeds on a flat floor as target satellite models. This system is a tele-operation ground experiment system and consists of the following subsystems: the robot system, vision system, manipulator operating system, ground control system and target satellite model system. Using this system, we will study on feasible operating methods of floating massive payload using dual-manipulators. In this paper, we explain the detailed description of the ground experiment system and report the results of fundamental experiments.

1 Introduction

It is expected that autonomous space robots conduct many on-orbit servicing, for example the construction and maintenance of large space structures as well as the capture and recovery of damaged satellites. In order to realize these missions, robot manipulators mounted on a satellite can be useful. In Japan, the Engineering Test Satellite VII (ETS-VII) was launched in 1997, and had experimented the robot operation technology as well as the rendezvous and docking technology until the end of 1999, which are indispensable to realize services in orbit. But there still exists many technical issues when an unmanned spacecraft deals autonomously with the rotational motion of an uncooperative satellite, for example, design of a grasping mechanism and control methods to approach and grip the target, and to reduce the relative motion between the target and chaser and so on. Thus, it is necessary to research on floating massive payload operation using robotic manipulators through both analytical and experimental approaches.

In this study, we have designed and integrated the ground experiment system in order to conduct the fundamental study in this field. The system consists of a dual-manipulator system fixed on the ground and a massive testbed floating on a large flat horizontal floor (3m x 5m). Each arm of the dual-manipulator system is a redundant 7-DOF human arm type and can be tele-operated by joysticks. Each end-effector has a grasp mechanism, a CCD camera, a laser displacement sensor and a six-axis force/torque sensor. This system uses the LAN(Local Area Network) for the communications between the ground station and the robot satellite. Therefore, we can introduce the random time lag in communication, which is one of the important problems in operating the satellites. The floating testbed can simulate the two-dimensional micro-gravity dynamics. This ground experiment system is very useful to study strategies and approaches to capture damaged satellites and operation of floating massive payload in space.

On the other hand, it is also important to supply the operator with necessary visual information from CCD camera. We propose coordinated vision control using dual-manipulator, and pursue an appropriate operation method to control one manipulator with a monitored CCD camera at the end-effector in cooperation with the other manipulator performing the required task.

In this paper, we explain the detailed description of the developed ground experiment system. We discuss in detail the experimental results of operation such as capturing the damaged satellite and operating the floating massive payload.
2 Ground Experiment System

Figure 1 shows the ground experiment system we have integrated in this study. This system is a tele-operation ground experiment system and consists of the following subsystems: the simulated ground station system, simulated robot (chaser) satellite system and simulated target satellite system.

The simulated robot satellite system consists of robot manipulator subsystem, mounted computer subsystem and vision system. The robot manipulator subsystem consists of a dual-manipulator, end-effectors and actuator control boxes. The dual-manipulators simulate space manipulators mounted on a chaser satellite, and are fixed on the ground, and each arm is a 7-DOF human arm type manipulator. The dual-manipulator can be operated with joysticks as shown in Figure 2. The end-effector has a grip mechanism, CCD camera, laser displacement sensor and six-axis force/torque sensor as shown in Figure 3. The grip mechanism is designed to grip handrails and/or a solar paddle beam of the simulated target satellite. The target satellite, whose mass is over 80kgs, is a floating testbed with handrails and simulated solar paddle. The flat floor is covered with a plate grass and has 3m×5m in area. The feature of this ground experiment system is combining the robot manipulator system and the simulated target satellite, which moves freely in the two-dimensional space.

This system uses the LAN (Local Area Network) for the communications between the simulated ground station and the robot satellite, and therefore can introduce the random time lag in communication, which is one of the important problems in operating the satellites. Figure 4 shows the communications architecture of this system.

Fig.1 Overview of the Ground Experiment

Fig.2 Schematic of the Ground Experiment System
3 Modeling and Formulation

One of the problems in robot satellite activity in orbit is that of attitude stabilization and control. This is particularly important when a robot satellite points to any arbitrary direction in space to keep communications and save powers. However, the space manipulators mounted on the satellite generate the attitude disturbance, and its level is much greater than the solar radiation pressure, aerodynamics torques and unbalanced thrust. Thus, the robotic arms may cause the difficulty in realizing their missions. There actually exist several researches on cooperative attitude control of the main satellite and space manipulators mounted on it[1], but some of them are hard to apply to actual space systems because the computer performance used in space is not high enough to compute their algorithms, and the trajectory of the robot manipulator is restricted so that various services in orbit cannot be provided. Oda[2] proposed the realistic method of cooperative attitude control of the Engineering Test Satellite VII (ETS-VII), which is the first satellite mounted the space manipulator in the world launched in 1997, and verified its effectiveness by experiments in orbit. In this section, we focus on the kinematic analysis and control of dual-manipulator and control system design to integrate the experiment system grounding on the facilities and the control system of the ETS-VII.

3.1 Kinematic Analysis of the Dual-Manipulator

Dual-Manipulators and Coordinate Systems

Figure 5 shows the coordinate systems used in kinematics analysis. The coordinate system fixed at the main satellite \( \{ b_0 \} \) is identical to the absolute coordinate system \( \{ i \} \) in this case, and \( \{ b_i \} \) and \( \{ b_i \} \) (\( i=1, \ldots, 7 \)) are \( i \)-th joint fixed coordinate systems of the right and the left manipulator, respectively. The subscripts \( r \) and \( l \) stand for parameters of the right and left manipulator, respectively.

![Fig.5 Coordinate systems on dual-manipulator](image-url)
Inverse Kinematics (I.K.)

where \( R_{\alpha \beta \gamma} \) is the rotation matrix, which is transformed to the Roll-Pitch-Yaw angles \( \theta_{\alpha \beta \gamma} \) as follows,

\[
R_{\alpha \beta \gamma} = \begin{bmatrix}
\cos \theta_{\alpha} & -\sin \theta_{\alpha} & 0 \\
\sin \theta_{\alpha} & \cos \theta_{\alpha} & 0 \\
0 & 0 & 1
\end{bmatrix} \quad \text{and} \quad \tilde{l}_{i} \in \mathbb{R}^{3} \ (i=0,\ldots,7) \text{ are link matrices in } \{b_{i}\}, \text{ respectively, which represent the relative position between the origins of } \{b_{i}\} \text{ and } \{b_{(i+1)}\}. \\

The end-effector attitudes \( R_{\gamma} \) and \( R_{\beta} \) with respect to \( \{b_{0}\} \) are obtained by the following relations:

\[
R_{\gamma} = \prod_{i=0}^{7} R_{\alpha \beta \gamma} \quad \text{and} \quad \tilde{l}_{i} \in \mathbb{R}^{3} \ (i=0,\ldots,7) \text{ are link matrices in } \{b_{i}\}, \text{ respectively, which represent the relative position between the origins of } \{b_{i}\} \text{ and } \{b_{(i+1)}\}. \\

The end-effector positions \( p_{b} \) and \( q_{b} \) are obtained from the joint angles \( \theta_{i} \) and \( \theta_{0} \) by the following relationships:

\[
p_{b} = l_{i0} + \prod_{k} l_{i4} \text{ where } l_{i4} = l_{i0} + l_{i1} + l_{i2} + l_{i3} + l_{i4} + l_{i5} + l_{i6} + l_{i7} \quad \text{(s=r, l)}.
\]

The end-effector position matrices \( p_{Er} \) and \( p_{El} \) are obtained from the joint angles \( \theta_{i} \) and \( \theta_{0} \) by the following relationships:

\[
p_{Er} = l_{i0} + \prod_{k} l_{i4} \text{ where } l_{i4} = l_{i0} + l_{i1} + l_{i2} + l_{i3} + l_{i4} + l_{i5} + l_{i6} + l_{i7} \quad \text{(s=r, l)}.
\]

Inverse Kinematics (I.K.)

The velocity equations are obtained from eqs.(3.1.1, 3) as follows,

\[
r_{s} = J_{s}(\theta_{s}) \dot{\theta}_{s} \quad (s=r, l),
\]

where

\[
r_{s} = \begin{bmatrix}
0_{6} \\
\end{bmatrix} \quad \text{and} \quad \dot{\theta}_{s} = \begin{bmatrix}
\dot{\theta}_{s} \\
\end{bmatrix} \in \mathbb{R}^{7}.
\]

The structures of the dual-manipulators are similar to human’s arms. Each manipulator has 7 joints and an end-effector that has a servo-control gripper, a 6-axis force-torque sensor, a laser displacement sensor and a CCD camera as described in the section 2.

Direct Kinematics (D.K.)

The end-effector position matrices \( p_{Er} \) and \( p_{El} \) in \( \{b_{h}\} \) are obtained from the joint angles \( \theta_{i} \) and \( \theta_{0} \) by the following relationships:

\[
p_{Er} = l_{i0} + \prod_{k} l_{i4} \text{ where } l_{i4} = l_{i0} + l_{i1} + l_{i2} + l_{i3} + l_{i4} + l_{i5} + l_{i6} + l_{i7} \quad (s=r, l),
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3.2 Kinematics Control of the Dual-Manipulators

In this study, we have implemented the following control modes examining the reports of the Shuttle Remote Manipulator System (SRMS)[3] and the manipulator mounted on the ETS-VII.

- Single Joint Mode
- Resolved Motion Rate Control (RMRC) Mode
- Visual Servo Mode

We have designed the control system of the dual-manipulators as the multi-layer control system. For example, the rotation control of joint actuators, which is the common and lowest layer control, is independent of the upper layer control, which is preferable in view of the software design. In our system, TITch Intelligent Drivers (TIDs)[4], which are programmable motor drivers, have been adopted as motor drivers.

Manipulator Control Mode

- Single Joint Mode
  A single joint mode is to control each joint angle. This mode is applied when a joint angle reaches its limitation and must return to the safety angle range.

- RMRC mode
  An RMRC mode is to control manipulators by a control command formed from the set of position (x, y, z) and attitudes (roll, pitch, yaw) data of the end-effector. This mode is normally applied to operate manipulators. This mode has a problem that an input rotation speed overflows when the configuration of the manipulator is singular. Our system stops and/or gives a warning to the operator when the configuration is getting singular. We use the measure of manipulability

  \[ \omega = \sqrt{\det JJ^T} \]  

  (3.2.1)

  defined by Yoshikawa[5] as the index of singularity.

- Visual Servo Mode
  The visual servo mode is to control manipulators by a control command based on the estimated position and attitude data of the target satellite by image processing. There are two types of visual servo mode in this study. The camera fixed on the main body is used for the first mode (type I), while the CCD camera fixed at each end-effector is used for the second mode (type II). These two modes are switched depending on the tasks. For example, in case of simulating the capturing process of the damaged satellite, the first type is applied when the target is relatively far from the robot satellite and switched to the second type when the target is close enough.

4 Fundamental Experiment

4.1 Fundamental experiments for satellite capturing and berthing

The right-arm is directly used for capturing the handrail of the satellite and berthing the satellite body, and visual information is obtained with the main camera installed on the dual-manipulator system body and two cameras equipped at each end-effectors. In this experiment, the left-arm is used for providing a movable vision which is a very important and vital tool in closely proxy tasks such as a capture operation. The following experiments are conducted in order to check the usefulness of the movable view by the left-arm (left hand-eye camera). Figure 6 shows the images used in the capture operation of the floating satellite by the right-arm end-effector. From the figures, the operator can judge the right end-effector situation, inspect the neighborhood of the handrail, and understand the grasping conditions. During the operation, the operators reported that the tasks are more easily accomplished even just before grasping. Figure 7 shows the data of (a) end-effector trajectory, (b) force/torque sensor output, and (c) distance between end-effector and handrail, and indicates the open/close states of the end-effector.

Fig.6 Visual information for operators
(Left: Left hand-eye camera, Center: Main camera, Right: Right hand-eye camera)
4.2 Fundamental operating experiments

We conduct the experiment simulated that captured target satellite is released. This experiment simulates transportation of the payload and de-orbit of the damaged satellites. We compared the operation by single arm and by dual arm. Figure 8 shows the data of attitude of the target, and force/torque sensor output.

On the operation by single arm, the angular velocity of the target satellite is produced and therefore the attitude of the target satellite fluctuates, because the center of gravity position cannot be accurately grasped. But, on the operation by dual arms, the target satellite can be more easily released without the fluctuation of the attitude. Therefore, it can be said that the operation by dual arms is more efficient than by single arm.

5 Conclusion

We explained the ground experiment system we have integrated for fundamental study of capturing and berthing methods of damaged satellites using the dual-manipulator. We also examined the satellite capturing method using camera images, which provides some hints for a feasible automatic capturing method. This system enables us to plan the efficient capture strategies and cooperative activities of the dual-manipulator in space.

References


