EXPERIMENTAL STUDY ON TWO-DIMENSIONAL FREE-FLYING ROBOT SATELLITE MODEL

Yoji UMETANI and Kazuya YOSHIDA

Department of Mechanical Engineering Science
Tokyo Institute of Technology
O-Okayama, Meguro, Tokyo 152, Japan

Abstract

This paper treats the experimental study on a control method for a free-flying space robotic arm by means of a two-dimensional laboratory model. The authors' main target is to develop a new control method for trajectory tracking or target capturing, considering dynamical interaction between the manipulator arm and the base vehicle in space micro-gravity environment. In order to simulate the micro-gravity environment mechanically, the authors develop a laboratory model of a robot satellite supported on air bearings. The model comprises a base equipped with power and air supplies and a two-link manipulator arm. This model has relatively low gravitational and frictional disturbance in planar motion. An on-line RMRC control scheme with vision feedback is developed for exprimenting capture operations. This scheme utilizes the Generalized Jacobian Matrix which was proposed by the authors in a previous paper. In experiment, the acceleration environment of the model is evaluated firstly, then target capture operations are examined. The manipulator can properly chase and capture both a standing target and a moving target in spite of complex satellite/manipulator dynamical interactions. The experimental results confirm the validity of the Generalized Jacobian Matrix concept and the proposed control method.

1. Introduction

For a successful development of space projects, robotization and automation should be a key technology. Autonomous and dexterous robot systems could reduce the workload of astronauts and increase operational efficiency in many missions. One major characteristics of these space robotic systems, which clearly distinguishes them from on-earth operated ones, is the lack of a fixed base. Any motion of the manipulator arm will induce reaction forces and moments in the base, which disturb its position and attitude. If the arm were controlled for such task as target capturing without provision for this base disturbance, it would fail in the task. To cope with this problem, some approaches for modeling and control of space manipulators have been suggested.

Lindberg, Longmann and Zedd [1] proposed a method for simultaneous control of manipulator and satellite attitude. They derived a model of the dynamically interacting satellite/manipulator system to generate decoupled commands for manipulator joints and moment compensation devices.

On the other hand, modeling and control methods for free-flying systems have been developed which do not provide any attitude control for the satellite main body during manipulator operation. Vafa and Dubowsky [2] introduced the Virtual Manipulator concept in order to describe geometrically free-flying mechanical links, using thereby simmilar expressions as for ground-fixed ones. They applied this concept to analyze work spaces, as well as to solve the inverse kinematics.

Umetani and Yoshida [3,4] introduced the Generalized Jacobian Matrix concept for the expression of the free-flying behavior at kinematic level. Kinematics and inverse kinematics problems at velocity level can be treated in a simmilar way as for ground-fixed systems, by replacing the conventional Jacobian with the proposed new matrix. The concept was applied for resolved motion rate trajectory tracking control.

As an experimental study, Alexander and Cannon [5] recently developed a free-flying satellite robot simulator model with an arm controller, based on the computed-torque method, and obtained good results.

This paper treats the experimental investigation on the control of space free-flying manipulator systems. A laboratory model was developed, which is based on the same design concept as in Alexanders' work. The control scheme of this model utilizes the Generalized Jacobian Matrix. Target capture operations can be successfully demonstrated.

2.Free-Flying Robot Satellite Model

2.1 How to Simulate Micro-Gravity Environment

How to simulate micro-gravity environment in on-ground laboratory: that's always a serious problem for ground test experiments of space assemblies. In general, the following 4 methods could be available for this purpose.

(1) Experiment in an airplane flying along a parabolic trajectory or a free-falling capsule. In this case, we can observe pure mechanical behavior under the law of nature, but it costs a lot and is inconvenient.

(2) Experiment in a water pool with the support of buoyancy. This is especially good for training of astronauts' activities.

(3) Experiment on an air-cushion or air-bearings. In this case, however, the motion is restricted on a plane.

(4) Calculate the motion which should be realized in micro-gravity environment by using a mathematical model, then force a mechanical model to move according to the calculation. This method is adopted for the FTS test bed [6].

Among them, (1)-(3) are mechanical methods and, (4) is called as a hybrid simulation method combining mechanical models and mathematical ones. Each method has advantages and disadvantages and, we should carefully select the method so as to satisfy the purpose of the experiment.

In this paper, the authors adopt method (3), because they would like to observe the behavior of mechanical link systems under the law of nature by the simplest apparatus. Simulators utilizing air bearings have been developed in U.S.A. The most famous one is the test bed of SRMS [7] . It is designed to test the practical validity of the arm controller but not to investigate the free-flying behavior. So, the arm is fixed on the ground at the shoulder joint. A simulator model for the investigation of the free-flying behavior has been developed by Alexander and Cannon in Stanford Univ. [5] . The present laboratory model is designed with the same concept as Alexanders' model.

2.2 Design Concept of the Laboratory Model

The authors' goal of the experiment is to analyze the behavior of a mechanical link system in micro-gravity environment and to verify the proposed control scheme. In order to accomplish such an experiment, the laboratory model should be completely free-flying, with no mechanical disturbances for planar motion. To realize it, the model is significantly required

(a) to install the air supply for air bearings, and

(b) to be controlled autonomously or remotely.

And, as additional requirements, the model is desirable to be not to large, as light as possible, and easy to manufacture.

A conceptual structure of the model which satisfies these requirements is shown in Fig.1. A robot satellite model that has 2 jointed-link manipulator, is supported by 3 air pads. Each joint is actively rotated by a DC motor but there is no actuator for attitude control of the satellite main body. As a light and compact air supply, liquidized-gas bombs are installed on the satellite main body. A remote measurement and control system consists of satellite mounted subsystems; a communication port and a PD servo-controller and ground facilities; a CCD camera hanging from the ceiling, a Video Tracker (VT) and a personal computer (PC). The control loop is described briefly as follows: Tip, joints and tail of the model and a target object are marked with light emitting diodes. The motion of the model and the target is monitored by the CCD camera. Video signals of LED marks are transformed into position data by the VT and transmitted to the PC via a GPIB communication line. Each control command for both actuators is calculated in the PC and transmitted to the satellite via a wire-less communication system. Manipulator joints are locally controlled by the on-board PD servo-controller according to the tele-commands.

Due to the air supply by gas bombs and the remote measurement and control system, the laboratory model avoids air-tubes or wire connections from the earth, and is able to float on thin air films without any mechanical disturbances or external accelerations.

2.3 Specifications

Detail specifications of the laboratory model are listed as follows:

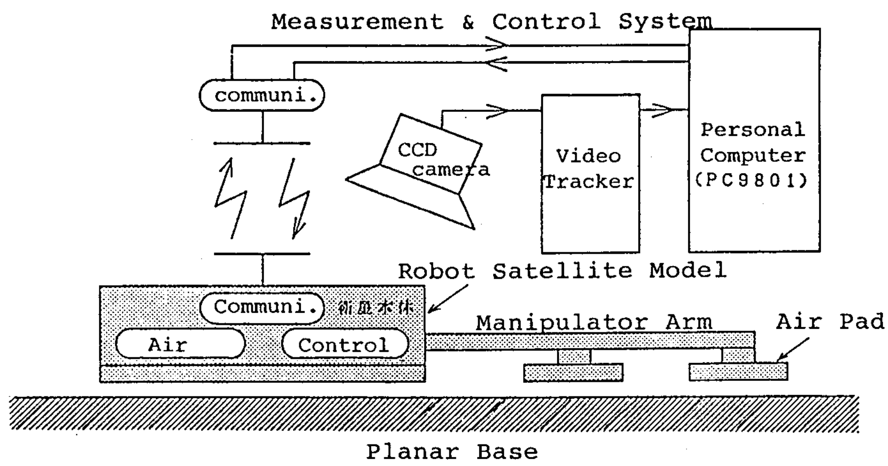


Fig.1. A conceptual structure of the laboratory model.

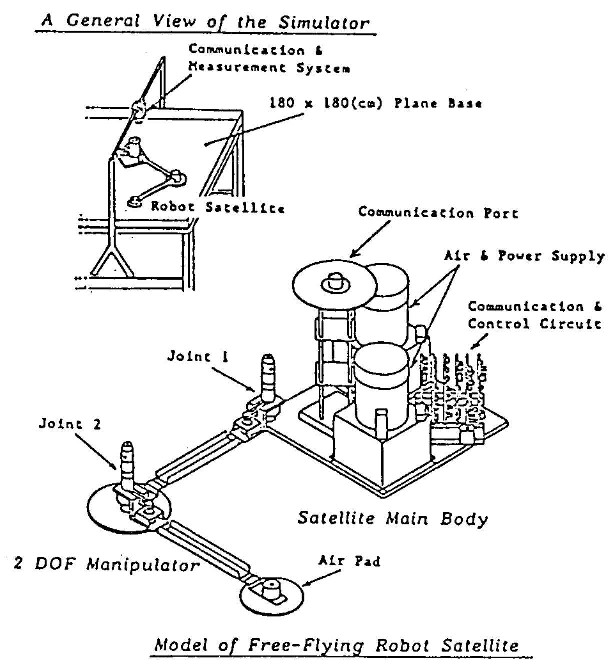
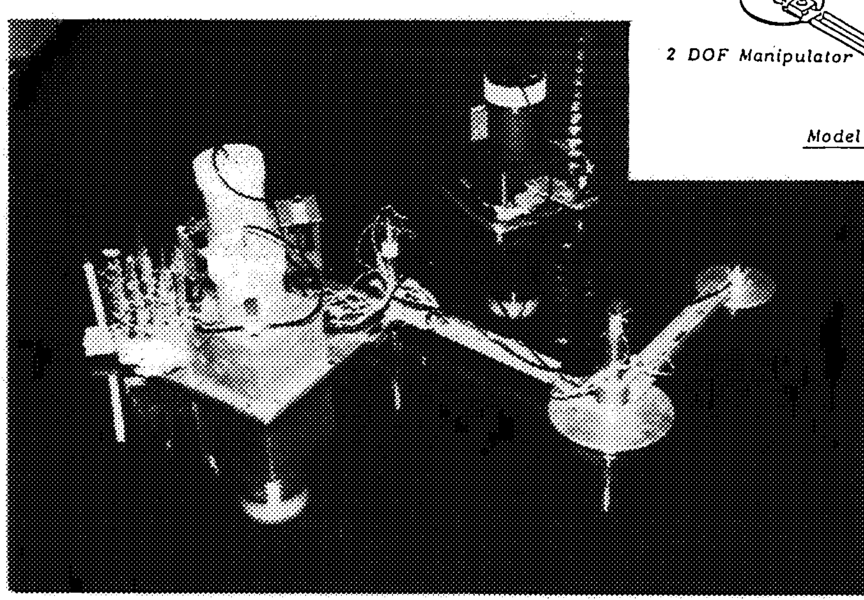


Photo 1 (↓) and Fig.2 (→).

A general view of the Robot Satellite model.



Robot Satellite

Satellite main body
- -dimension: 300x300mm
- -weight: 6.3 kg
- -equipments: gas-bomb type air supply
  rechargable battelies
  wire-less communication system
  local servo-controller

Manipulator
- -dimension: 700mm (350mm for each link)
- -weight: 1.4 kg
- -actuator: DC motor+planetary gear train
- -sensors: potentio-meters
  tacho-generators

Ground Facilities

Planar base table
- -dimension: 1800x1800mm
- -material: planar glass with multi-supports

Measurement and control system
- -512x492 CCD camera (NEC)
- -Video Tracker (G-3100:OKK Inc.)
- -16bit personal computer (PC-9801-VM2:NEC)

Photo 1 and Fig.2 show a general view of the developed laboratory model. Detail dimensions and inertia parameters of each link are listed in Table 1.

body No.	0	1	2
a (m)	0.190	0.162	0.124
b (m)	0.190	0.188	0.226
m (kg)	6.256	0.747	0.620
I (kgm^2)	0.169	0.0424	0.0141

Table 1. Dimensions and inertia parameters of each link.

3.Modeling and Control

An on-line resolved motion rate control (RMRC) scheme with vision feedback is developed for target capture operation by using the Generalized Jacobian Matrix (GJM). In this section, firstly the derivation of a mathematical model and the GJM is described, then an on-line control scheme is introduced.

3.1 Generalized Jacobian Matrix

A mathematical model and notations which correspond to the laboratory model are described in Fig.3. Bodies are numbered consecutively with "0" being the satellite main body and "2" the manipulator end-link. Tip position vector p and mass center of each link r_i are described with respect to the origin of the inertial coordinate system. Only planar motion in X-Y plane and rotation around Z axis are considered in this paper.

For such a free-flying system, the momentum conservation equations hold true:

$$\sum_{i=0}^{2} m_i \dot{r}_i = \text{const.} \tag{1}$$

standing for translational momentum, and

$$\sum_{i=0}^{2} (I_i\omega_i + m_i r_i \times \dot{r}_i) = \text{const.} \qquad (2)$$

for rotational momentum, respectively. In these equations, m_i is the mass of body i, ω_i-its angular velocity and I_i -its inertia matrix. Eq.(2) can be rewritten as

$$I_s\dot{\Omega} + I_m\dot{\Phi} = 0 \qquad (3)$$

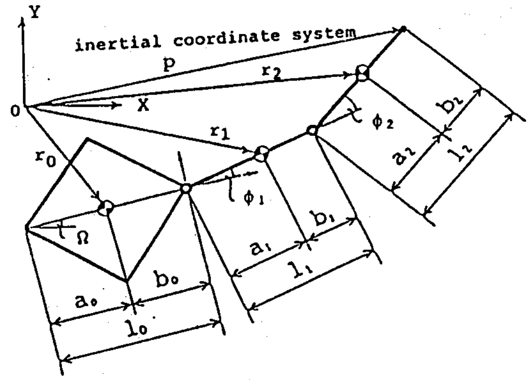


Fig.3. A mathematical model.

to distinguish the satellite rotational momentum $I_s\dot{\Omega}$ from the manipulator one $I_m\dot{\Phi}$, where $\dot{\Omega}$ is the attitude angular velocity and $\dot{\Phi}$ is the 2 x 1 joint velocity vector and I_s , I_m are defined in the Appendix. Initially, the system is assumed to be at rest, i.e. the right term of eq.(3) representing the initial momentum of the system is assumed to be zero.

On the other hand, for any manipulator, the relationship between the endtip velocity vector $\dot{p}$ and the joint velocity vector $\dot{\Phi}$ can be represented by the well known linear equation

$$\dot{p} = J\dot{\Phi} \qquad (4)$$

J being a Jacobian matrix. In the case of a satellite mounted manipulator, eq.(4) can be rewritten as

$$\dot{p} = J_s\dot{\Omega} + J_m\dot{\Phi} \qquad (5)$$

to distinguish the satellite-motion dependent endtip velocity $J_s\dot{\Omega}$ from the manipulator-motion dependent one $J_m\dot{\Phi}$. The satellite Jacobian J_s and the manipulator Jacobian J_m are defined in the Appendix. Note that both are functions of mass distribution in the satellite/manipulator system. From eqs. (3) and (5), we can eliminate the uncontrolled Ω variables:

$$\dot{p} = J^*\dot{\Phi} \quad ; \quad J^* = J_m - J_s I_s^{-1} I_m . \qquad (6)$$

J^* is named <u>the Generalized Jacobian Matrix</u> for satellite mounted manipulator arm.

An important result with the GJM is that the conventional control scheme for ground-fixed manipulators is directly applicable for space free-flying ones by replacing J with J^* . For example, a Resolved Motion Control scheme for free-flying manipulators is simply described with the inverse of J^* as

$$\dot{\Phi}_d = [J^*(\Phi)]^{-1}v \qquad (7)$$

where v is the commanded endtip velocity and $\dot{\Phi}_d$ is resolved joint velocity command. This scheme could properly control trajectory tracking or target capture operations, taking into account the satellite/manipulator dynamic interactions.

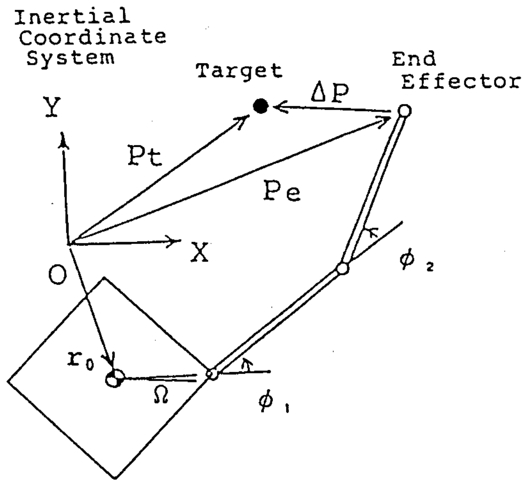


Fig.4. Parameter description for target capture operation.

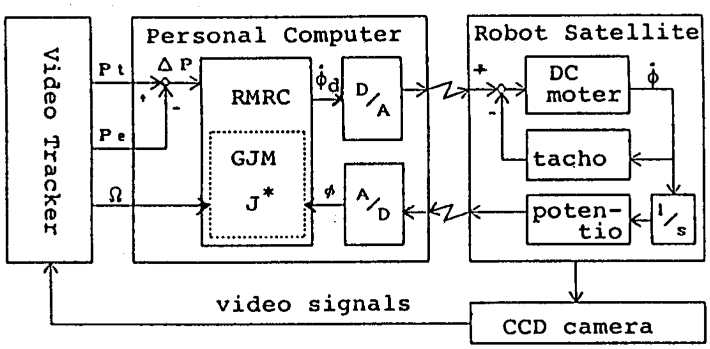


Fig.6. Control block diagram.

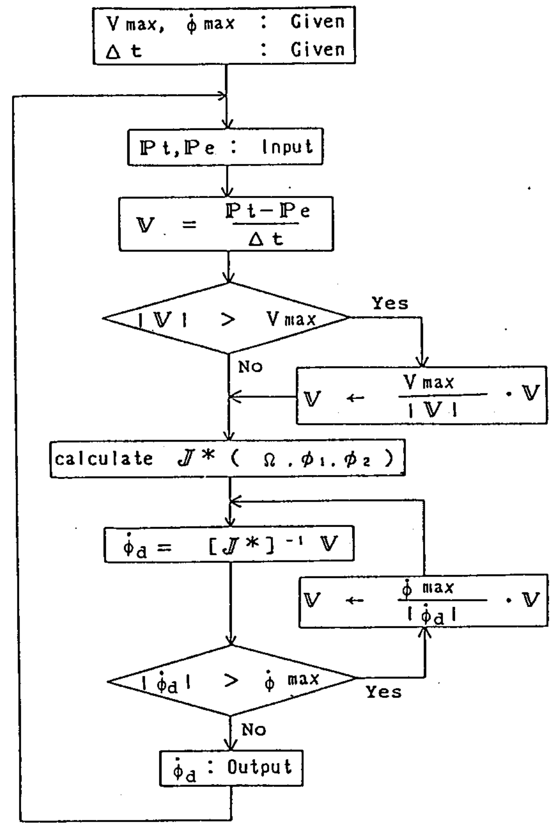


Fig.5. Control flow-chart.

3.2 On-line RMRC Scheme based on the Generalized Jacobian Matrix

Parameters needed for capture control are defined in Fig.4. The following values are assumed to be measured at each sampling interval Δt during the operation: Ω -satellite attitude, ϕ_1, ϕ_2 -manipulator joint angles, p_e-position of manipulator endtip, and p_t -position of the target. Endtip velocity command v is determined with a position error vector $\Delta p = p_e - p_t$ by

$$v = \frac{\Delta p}{\Delta t} = \frac{p_e - p_t}{\Delta t} . \qquad (8)$$

This value is then substituted in eq.(7), to obtain joint operation commands $\dot{\Phi}_d$.

A flow-chart of this scheme with an appropriate data scaling process for avoiding high joint velocities near singular points, is shown in Fig.5. Also a block diagram is presented in Fig.6. The values of p_e , p_t and Ω are measured by the Video Tracker with video signals. Joint angles Φ are measured by potentiometers located at manipulator joints and transmitted via the tele-communication system. The generalized Jacobian Matrix is calculated with Ω and Φ , then the joint velocity commands are determined by the above mentioned procedure. The commands are transmitted to the robot satellite and joints are controlled with a local velocity feedback. Note that the designed control scheme is based on the vision data from the ground-fixed CCD camera, however, it is equivalent to measure p by a satellite mounted camera and by an on-board sensor. It means that this control scheme can be easily installed on the satellite.

Given conditions for the following experiment are:

maximum tip velocity	v_{max}	: 0.1 m/sec,
maximum joint velocity	$\dot{\phi}_{max}$	: 15.0 deg/sec,
data sampling interval	Δt	: 0.2 sec.

In this case, position sensing by the VT requires 1/30 seconds and more than 0.1 seconds are spent for the calculation of the GJM and its inversion. The calculation is executed by i8086+8087 processors using C language.

4.Experimental Results

4.1 Arm Slewing Maneuver

As a preliminary experiment, the measurement of friction between the planar base and air pads and an arm slewing maneuver have been made. The friction of air films is due to the viscosity of the air and is unavoidable. The order of the friction coefficient $\mu = \alpha$ (horizontal acceleration)/ g (vertical acceleration) is measured as 10^{-3}. In other words, the laboratory model is allowed to work in 10^{-3}g acceleration environment.

Fig.7 shows the experimental result of an arm slewing maneuver. In Fig.7 (a) the mass center of the system, which should be stationary during the maneuver, is a little bit moving, and in Fig.7 (b), the measured satellite attitude (in solid line) has also a small error from the calculated one by eq.(3) (in dot line). However, if the friction effect is considered, the momentum conservation will be proved, and the relationship between joint velocities and tip velocity described by eq.(6) will be also true during the maneuver. This fact shows the validity of the Generalized Jacobian Matrix concept.

4.2 Capture of a Standing Target

Capture operations of a standing target are successfully accomplished by the simple rate control with the GJM. Fig.8 shows a typical result of the operation. From the initial point to the target, the manipulator endtip travels straight and smoothly in spite of a large satellite attitude change.

4.3 Capture of a Moving Target

As for a smooth chase and capture of a moving target, the endtip velocity command is modified by the information of the target velocity $\dot{p}_t$.

$$v = \frac{p_e - p_t}{\Delta t} + \dot{p}_t \qquad (9)$$

With this small modification, the manipulator works very well for capture operations both of a standing target and a moving target. Fig.9 shows a typical experimental result of the capture of the moving target with $\dot{p}_t$= 0.05m/sec.

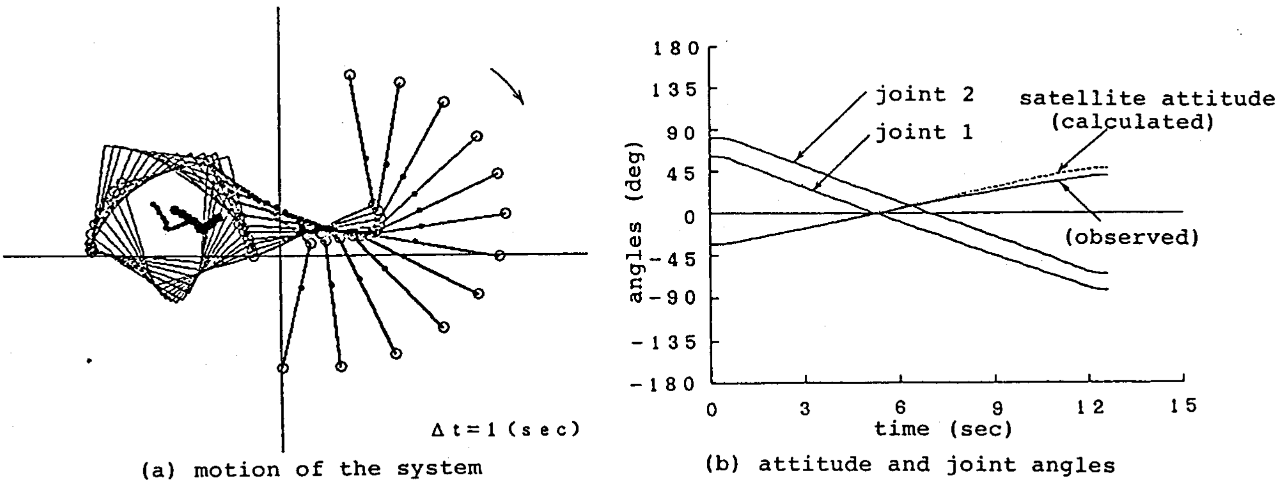


Fig.7. Arm slewing maneuver.

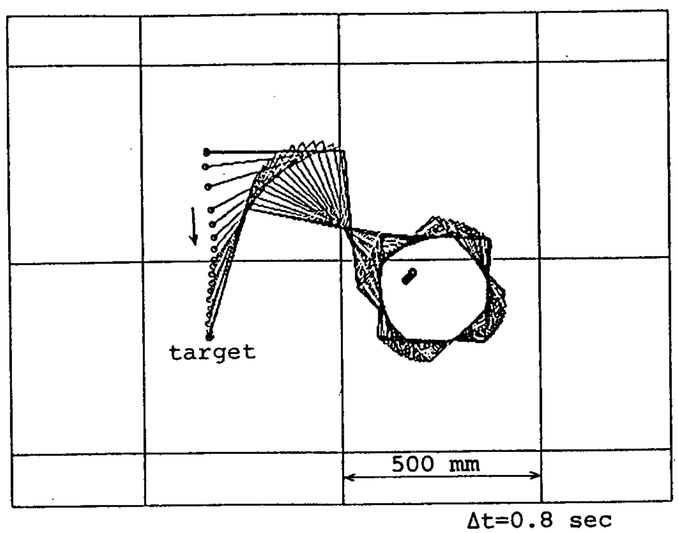


Fig.8. Capture of a standing target.

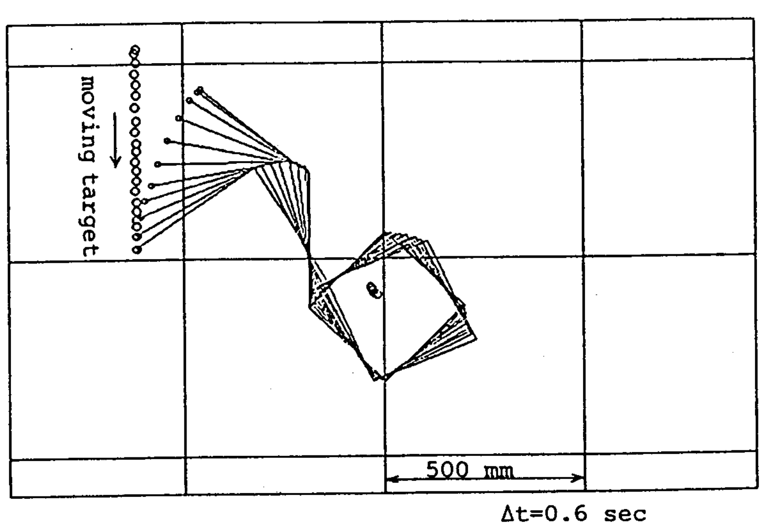


Fig.9. Capture of a moving target.

5.Conclusions

This paper presents the experimental investigation on the control of a space free-flying manipulator system. In order to simulate the micro-gravity environment, a laboratory model of a robot satellite supported on air bearings, is developed. The model is evaluated to have relatively low gravitational and frictional disturbance (of order 10^{-3}g) for planar motion. An on-line RMRC scheme with vision feedback is developed for experimenting capture operations. This scheme is based on the Generalized Jacobian Matrix concept. Through experiments, it has been shown that the manipulator is able properly to chase and capture both a standing target and a moving target, in spite of the complex satellite/manipulator dynamical interaction. The results confirm the validity of the Generalized Jacobian Matrix concept and the proposed control method. Advantages of the approach are the relatively simple algorithm and the possibility for easy installation on practical systems.

Appendix

The matrices I_s, I_m, J_s and J_m are defined as follows:

$$I_s=h_0+h_1+h_2+2C_{01}+2C_{12}+2C_{20},$$
$$I_m=[h_1+h_2+C_{01}+2C_{12}+C_{20},\ h_2+C_{12}+C_{20}]$$

where

$$h_0=I_0+M_0b_0^2, \quad h_1=I_1+M_0a_1^2+M_2b_1^2+2M_1a_1b_1, \quad h_2=I_2+M_2a_2^2,$$
$$C_{01}=(M_0b_0a_1+M_1b_0b_1)\cos\phi_1, \quad C_{12}=(M_1a_1a_2+M_2b_1a_2)\cos\phi_2, \quad C_{20}=M_1b_0a_2\cos\phi_1+\phi_2,$$
$$M_0=m_0(m_1+m_2)/w, \quad M_1=m_0m_2/w, \quad M_2=(m_0+m_1)m_2/w, \quad w=m_0+m_1+m_2.$$

$$J_s=[-(s1+s2+s3)\ \ c1+c2+c3\ ]^t,$$
$$J_m=\begin{bmatrix} -(s2+s3) & -s3 \\ c2+c3 & c3 \end{bmatrix},$$

where

$$s1=m_0b_0\sin\Omega/w, \quad c1=m_0b_0\cos\Omega/w$$
$$s2=(m_0l_1+m_1b_1)\sin(\Omega+\phi_1)/w, \quad c2=(m_0l_1+m_1b_1)\cos(\Omega+\phi_1)/w,$$
$$s3=[(m_0+m_1)l_2+m_2b_2]\sin(\Omega+\phi_1+\phi_2)/w, \quad c3=[(m_0+m_1)l_2+m_2b_2]\cos(\Omega+\phi_1+\phi_2)/w.$$

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