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Functional Test Model and Verification Experiments of Docking Mechanism for Mothership-Daughtership Nano-Satellites

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Abstract

In this paper, a docking mechanism is proposed for a mothership-daughtership nano-satellite, and a docking methodology using grasping phase and guiding phase is investigated. During the grasping phase, the mothership grasps the daughtership even though the daughtership has relative position and attitude control errors as well as relative velocity in a docking space. During the guiding phase, the mothership guides the daughtership to a docking port while adjusting its attitude in order to transfer electrical power and fuel to the daughtership. The mechanism is designed to have grasping and guiding functions that realize the proposed methodology. A functional test model of the docking mechanism is fabricated for verification experiments and we conducts docking experiments in 3-demensional microgravity environment using a free-falling drop capsule at Japan Microgravity Center (JAMIC). In the experiment, we use a nano-satellite model with gas thrusters and a reaction wheel. This paper discusses the microgravity experimental setup and its results.

1. Introduction

In the near future, in-orbit servicing systems are expected to conduct inspections, observations, capture, recovery, repair and de-orbit of uncontrolled satellites, and to construct large-scale structures like the International Space Station and solar power satellite systems. The authors proposed a tethered mothership-daughtership satellite system as one of the in-orbit servicing systems [1]. The authors had participated in MDS (Mission Demonstration test Satellite) project, which conducts fundamental experiments using mothership- daughtership satellites since 1998 with Hokkaido Institute of Technology (HIT), University of Tokyo, NASDA, Astro Research and Tokyo Institute of Technology [2][3]. Docking technology is an important technology for the in-orbit servicing systems because autonomous connection and separation between satellites, space robots and assemblies will be required for these services.

Docking technology has been researched since 1960's. For example, the Apollo spacecraft docking system is very reliable for manned space flight and the principal components are: a drogue, a probe, latches, a tension tie and a docking ring. The system did not need an onboard control system because the astronauts complete the docking procedure. This type of docking system is not suitable for autonomous small/nano-satellite docking. Other docking systems for manned space flight, such as International Space Station, Soyuz, Mir and so on, are similar to the Apollo docking system. ETS-VII docking system for unmanned spacecraft, which was developed by NASDA, is an excellent autonomous docking system but the system needs a high accurate onboard control system with many dedicated sensors such as rendezvous radars, GPS receivers and proximity sensors. An example of this docking mechanism is the grapple fixture for the Canada arm on the Space Shuttle.

For the docking system of a mothership-daughtership nano-satellite, we considered the following issues, (1) the mothership has docking equipment, (2) the daughtership's actuators and sensors are utilized for docking, (3) the daughtership should dock reliably with the mothership under the conditions that its control is not accurate and docking alignment is needed to recharge and refuel, (4) size and weight budgets are limited. Therefore the conventional docking systems cannot be used for the mothership-daughtership nano-satellite. Thus, our laboratory has studied and developed docking system for the mothership-daughtership nano-satellite.

This paper introduces the new docking system, which includes a methodology, mechanism. This paper also includes an explanation of design of the mechanism and the functional test model used conduct verification experiments with a control algorithm. Finally we report the 3-dimensional microgravity experiments performed with HIT. The experimental system consists of a docking mechanism, a nano-satellite, CCD camera and so on. In the experiments, we verify the grasping function and the guiding function of the proposed docking methodology.

2. Docking Methodology

2.1 Mothership-Daughtership Satellite System

Mothership-Daughtership satellite systems will consist of a mothership and several daughterships [3]. The satellite system will be launched together and the daughterships separate from the mothership to accomplish various tasks. Requirements for the small-satellite mothership which will act as a base ship will be the following: (1) to firmly hold the daughterships launch, (2) to conduct repeated docking and separation of several daughterships, (3) to communicate with the daughterships, and (4) to recharge and refuel the daughterships. Requirements for the nano-satellite daughterships which will act as the worker ships will be the following: (1) to fly around a target and inspect it, (2) to communicate to the mothership.

We focused on the docking mechanism for the mothership-daughtership satellite in the paper.

2.2 Requirements of Docking Mechanism

The main purposes of a docking mechanism are to repeatedly dock and release a daughtership stably, as well as to align a daughtership with a docking port in order to recharge and refuel it. For a small/nano satellite, the mechanism must be a small, lightweight, simple and low-powered. The size of the daughtership is a cylinder whose dimensions are 200mm-diameter and 300mm-height and it has an attitude control system with micro reaction wheels and micro gas jet thrusters as well as CCD Cameras for satellite guidance [3]. An approximate size requirement for the mechanism is a 400mm-diamter and 400mm-height cylinder with a weight requirement of less than 15kg and a power consumption is about less than 50W (24V).

2.3 Concept of Docking Methodology

We proposed the new docking methodology for mothership-daughtership nano-satellite system. It focuses on the final approach phase, docking phase and separation phase of all rendezvous docking procedures [5]. Figure 1 indicates a schematic of the proposed docking methodology.

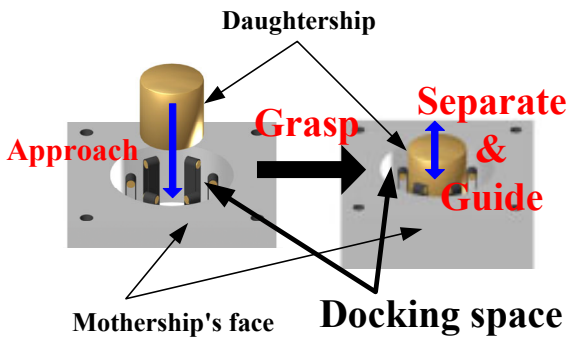


Figure 1 Schematic of Docking Methodology

The proposed docking phase is divided into two phases. Phase 1 is a grasping phase. In this phase, the daughtership approaches a docking space inside the docking mechanism. The docking space is large enough to permit position and attitude control error of the daughtership, and the docking mechanism is able

to grasp the daughtership even if it has relative velocity and control errors in the docking space. Phase 2 is a guiding phase. During this phase, the docking mechanism guides the daughtership to a docking port while adjusting the daughtership's attitude. The docking mechanism can also separate the daughtership with attitude and speed control using the same mechanism of phase 2. In this methodology, the docking system is able to dock without utilizing high control accuracy or using delicate sensors, and daughtership doesn't need any special mechanisms such as a grapple fixture.

3. Docking Mechanism

3.1 Design of Docking Mechanism

We designed a docking mechanism to verify the proposed methodology. It is important to realize the two phases while meeting the size/weight requirements. We designed the docking mechanism by making the grasping and guiding functions as the key functions.

1) Grasping function

The grasping function is able to grasp the daughtership while allowing for errors in the daughterships position and attitude. The docking space is a 300mm-diameter and 300mm-height cylindrical shape. The daughtership is a 200mm-diameter and 200mm-height of cylinder.

2) Guiding function

The guiding function guides the daughtership to the docking port while adjusting its attitude. The guiding function can also separate a daughtership using the same mechanism.

Figure 2 indicates a schematic of the mechanism design. The mechanism has a bottom part and six grasping finger parts. The bottom part which is able to translate the six grasping fingers consists of bevel gear on the center of the mechanism and ball screws placed radially. The grasping parts are located a concentric circle in order to grasp the daughtership. Each part has five rollers to guide and release the daughtership. The rollers of the grasping fingers are rotated by a DC motor with timing belts. Each part is connected to a ball screw. They can be opened and closed synchronously by the ball screws by rotating one bevel gear. Figure 3 indicates open and close configurations.

All actuators used to rotate the rollers and the bevel gear are driven and controlled by DC motors with costumed motor drivers. The motor driver (called Titech Intelligent Driver, TID) can control angle, angular speed and current of DC motors through serial communications (TIA/EIA-485). The motor drivers provide a lighter harness system than before.

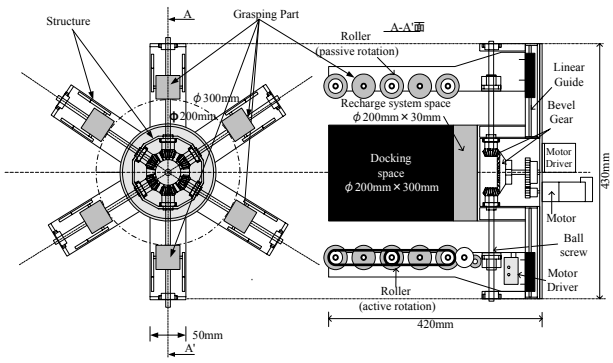
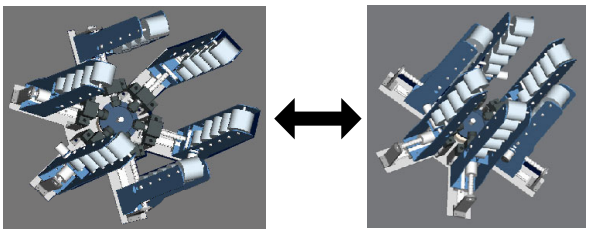


Figure 2 Schematic of Design Result



Open configuration Close configuration

Figure 3 Open/Close Configuration

3.2 A Functional Test Model

A functional test model is shown as Figure 4. The objectives of the model are to confirm whether or not all mechanisms will work well and whether the implemented motor control algorism is reliable. Thus the model consists of essential parts that verify the key functions. The model has the following: (1) only three grasping parts are enough to realize the grasping and guiding functions, (2) three docking detect sensors on bottom of the mechanism and three open limit sensor on each grasping part, and (3) laser relative distance measurement sensors (distance sensors), which consist

laser displacement sensors used to measure the relative distance between the docking mechanism and the daughtership, on the bottom of the mechanism.

The size envelope of the model is 430mm-diameter and 420mm-height in cylinder (includes 270mm-diameter and 300mm-height for a docking space). The total weight is 16.4kg. The power consumption is about 12W (24V). Additionally, some magnesium alloys are used as structure material in order to realize the lightweight system requirements.

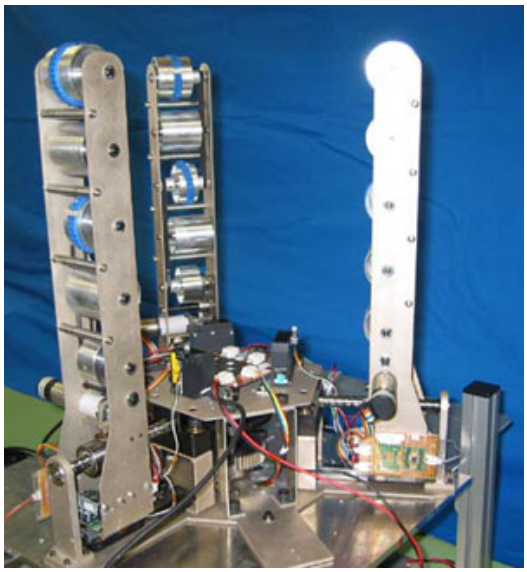


Figure 4 Functional Test Model

3.3 Control Algorithms

We consider the practical control algorithms, especially the grasping function. Figure 5 indicates a flow chart of the grasping function control algorithm.

The grasping function has three check routines. The first routine is called Close Start Check. The routine judges whether a daughtership comes into the docking space by using of the value of the distances between two satellites. The mechanism starts to close the grasping fingers when a daughtership comes into the measuring range of the sensors. The second routine is called Current Check. This routine judges whether or not the docking mechanism can grasp the daughtership firmly using the current value of DC motor to rotate the bevel gear. The control mode of DC motor is managed by the routine. The control mode is speed control that watches the current value of DC motor while the docking mechanism closes the grasping fingers. The control mode is changed from speed control to current control as soon as the current value is higher than a previously set threshold value. The third routine is Attitude Check. This routine confirms whether or not the attitude of the daughtership is accurate using the value of a diameter of the docking space after the second check routine of this control algorithm. If the attitude of a grasped daughtership is bad, the mechanism avoids grasping the daughtership and returns to the initial condition. The docking mechanism automatically grasps the daughtership certainly by using three check routines.

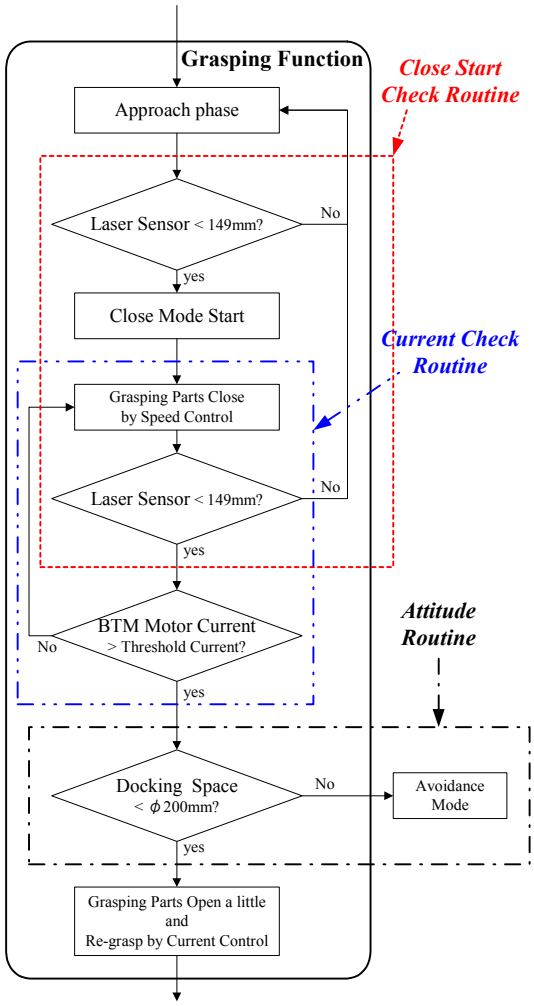


Figure 5 Grasping Function Control Algorithm

The guiding function is not as sophisticated. The control mode of the motor to rotate the bevel gear operates in current mode during the guiding function. The current control corresponds to control of a grasping torque. By controlling the grasping torque, the mechanism can adjust the attitude of the daughtership while it guides and separates the daughtership. The control mode used to rotate rollers on each grasping part is speed control. The speed control of rollers is used to control the guiding and separating speed.

4. Verification Experiments

4.1 Overview

We conducted three types of experiments. The first experiment is a functional evaluation experiment in which we confirm whether or not all the mechanisms can move smoothly and that implemented motor control algorism is reliable. The second is a two-dimensional microgravity experiment using the floating satellite simulators developed in our Lab that can be controlled both the position and the attitude using air thrusters [4]. In this experiment, we verify the grasping function, measure the permissible grasping space, and evaluate the control method of grasping and guiding. The guidance, navigation and control of the mothership and the daughtership are also important research issues. The third is a free-fall type microgravity experiment at Japan Microgravity Center (JAMIC). In the experiment, a relatively good microgravity environment (about $1.5e^{-3}$G) is achieved for 10s, and we verified the grasping function under the microgravity environment.

This paper explains the newest 3-dimensional microgravity experiments with HIT in December 2002. Please refer to [2][6] for other experiment results.

4.2 3-Dimensional Microgravity Experiments

We have conducted 3-dimensinonal microgravity experiments six times since 2001. In the past four times, we only verified whether the mechanism could grasp a daughtership using a simpler control algorithm than mentioned above. The daughtership was developed by our laboratory and didn't have control devices. The differences between the latest two experiments and the others are the following: (1) We conducted the experiments with HIT, who developed a daughtership model with two thrusters and one reaction wheel. (2) The space of the experiment rack is the biggest of the JAMIC experiment facilities. The size is W870mm x L870mm x H918mm. The size is big enough so that the daughtership approaches the docking mechanism while controlling its speed and attitude. (3) We completely verified the grasping function of this functional test model in the experiments.

The experiment system, which was made by HIT and our laboratory, is shown in Figure 6. The right side of the rack is our preparing system and fixes the docking mechanism and support system for the mechanism. The left side is the HIT preparing system and fixes nano-satellite and release mechanism for nano-satellite. There are 7 cameras to monitor behavior of the docking mechanism, nano-satellite and release mechanism for satellite. The images of the seven cameras are used for image processing in order to analyze the motion of nano-satellite.

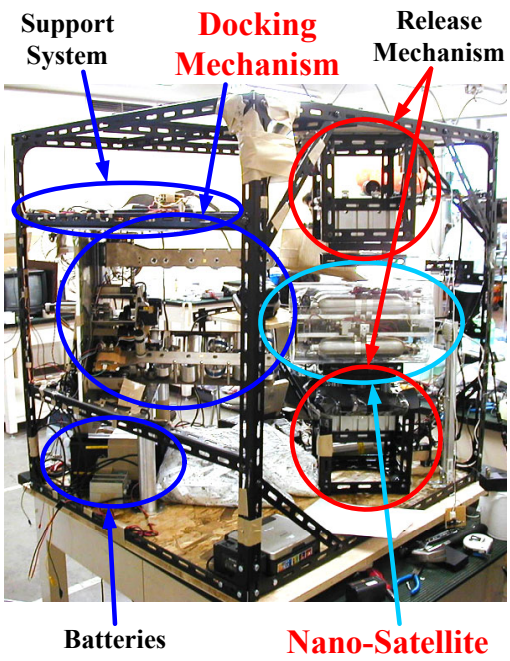


Figure 6 Experiment System

The system is turned on by the signal from the JAMIC operation room at –3s from the drop time. The drop capsule drops from 0s to about 10s. The nano-satellite, which is developed by HIT, starts the initialization of satellite control system at –2.5s and starts to control its reaction wheels and thrusters at 3.5s after releasing from the release mechanism at 2.5s. The docking mechanism receives the start signal bit at 0s from the timer circuit. The mechanism is synchronized with the timer circuit of the experiment system. The docking mechanism starts to control the grasping function as soon as it receives the signal bit. The mechanism closes the grasping fingers when the nano-satellite comes into the docking space and it guides the nano-satellite after grasping it completely. The mechanism continues to the guide nano-satellite until 8.5 and separates it in order to prepare for the braking the capsule. The nano-satellite drops onto the shock absorber after the separation.

4.3 Experiment Result

First, we will explain the event sequence evaluated from the acquired images shown in Figure 7.

The event sequence is the following: the capsule starts to drop at 0.0s, the nano-satellite is released at 1.97s, the mechanism starts the close motion at 5.27s, the mechanism grasps completely at 7.00s, the mechanism starts to guide at 8.03s, the mechanism separates nano-satellite at 8.67s, the capsule is braked at 9.70s, the dropping nano-satellite collides with the grasping fingers of the mechanism at 9.72s.

Figure 8 shows the microgravity level in the experiment. The vertical axis indicates a microgravity level whose unit is the gravitational acceleration and the horizontal axis indicates the passage of time from the start of dropping whose unit is second. An average microgravity level is kept at $1.9e^{-3}$g but the level fluctuates from 2.0s to 2.5s, from 5.0s to 7.0s. The first fluctuation corresponds to the time when release mechanism releases the nano-satellite. The second fluctuation corresponds to the time when the docking mechanism closes the grasping fingers.

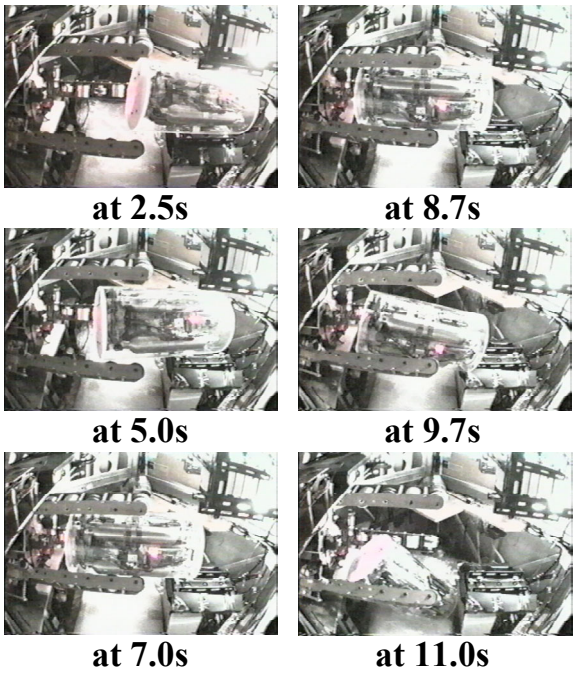


Figure 7 Slides of CCD Camera Images

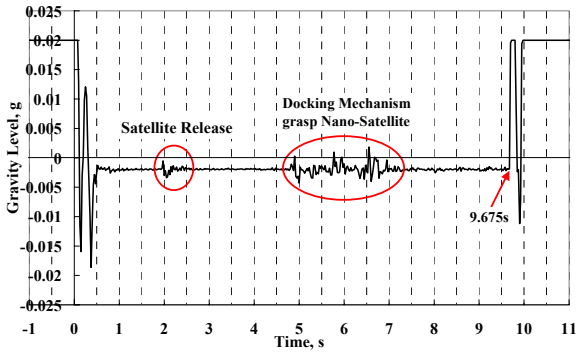


Figure 8 Microgravity Level

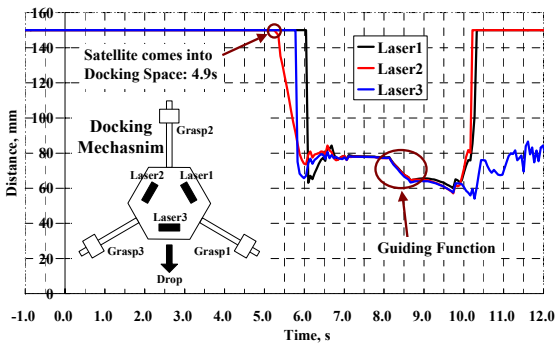


Figure 9 Distance Sensors

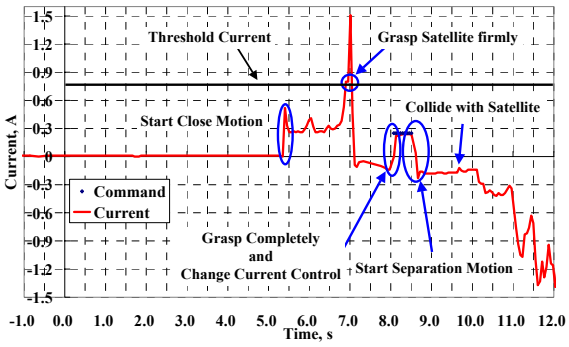


Figure 10 Current Motor to Translate the Grasping Finger Parts

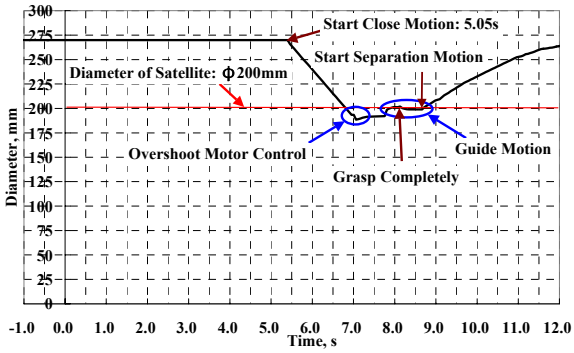


Figure 11 Diameter of Docking Space

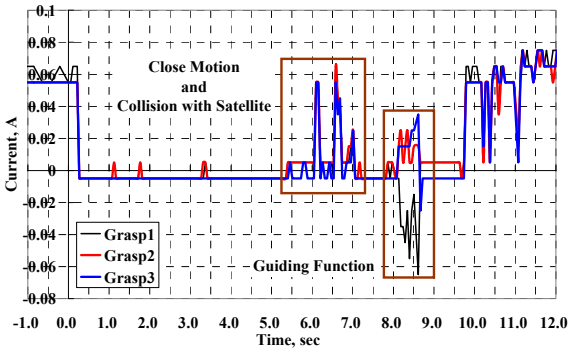
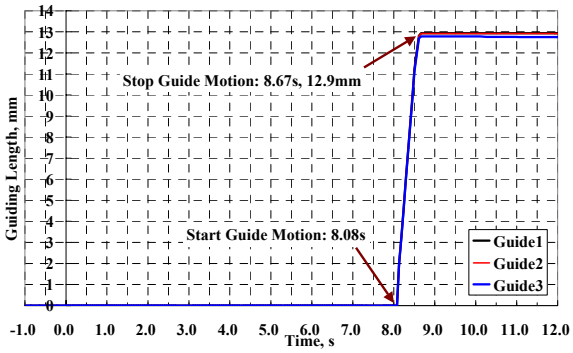


Figure 12 Motor Current used to rotate rollers



Finger 13 Guiding Length

The values of the three distance sensors are shown in Figure 9. The vertical axis indicates the distance between the docking mechanism and nano-satellite. The location of each grasping part and each distance sensor is seen on the figure. Motor current needed to translate the grasping fingers is shown in Figure 10. The vertical axis indicates current whose unit is ampere. The diameter of the docking space is shown in Figure 11 and the unit of the vertical axis is millimeter. Figure 12 indicates the motor current used to rotate the rollers on each grasping fingers and Figure 13 indicates a guiding length calculated from the rotation angle of the motor on each grasping fingers. The horizontal axis of all figures is the same as Figure 8. The docking mechanism detects that the satellite comes into a docking space at 4.9s in Figure 9 and starts to close the grasping fingers from 4.9s to 7.0s in Figure 10 and 11. Motor Current is higher than the threshold current at about 6.9s in Figure 10. However, the mechanism overshoots the motor control and grasps the satellite too strongly because the period needed to change to the speed control mode is too long. The mechanism grasps the satellite completely and the motor control mode changes from speed control to current control in Figure 10 and 11. The mechanism guides the satellite from 8.1s to 8.7s in Figure 9 and 13. The guiding length is about 14.0mm in Figure 9 and is about 12.9mm in Figure 14. The reasons for the difference between the value in Figure 9 and in Figure 14 is due to the modeling errors of motor and gear system on the grasping fingers as well as the influences of the friction, stick and slip, between roller and satellite. The value of grasping part 1 is the maximum of the absolute motor current in Figure 12 and the value of the grasping finger 3 is larger than the one of the grasping finger 2 in Figure 12. The reason for these results is that the satellite goes into the space between the grasping part 1 and the grasping part 3. This behavior is confirmed from the images of CCD camera. The mechanism starts the separation motion from 8.6s.

5. Concluding Remarks

This paper explained the proposed docking methodology, the designed docking mechanism and the fabricated functional test model using the control algorithm for grasping and guiding. We have developed the experiment system of JAMIC with Hokkaido Institute of Technology. We found the following results from the experiments: (1) The docking mechanism grasps the nano-satellite with the grasping fingers. (2) The mechanism guides the satellite smoothly using the rollers of the grasping fingers. (3) The control algorithm is useful for grasping and guiding. (4) We can estimate the attitude of the grasped nano-satellite by comparing with the motor currents of the grasping fingers.

We will study and develop the following: (1) We will modify the control algorithm. The mechanism needs to grasp a daughtership softly in order to reduce damage on the structure of the daughtership and guide the daughtership while adjusting its attitude. (2) We will model a docking mechanism and a daughtership in order to simulate the docking behavior using multibody dynamics with impact, stick, slip and friction. We will redesign the docking mechanism and the control algorithm to make use of results gained from the design, experiments and analyses. Additionally, we will consider other docking systems, especially the guidance, navigation and control of rendezvous phase as well as a refuel system.

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