Grasping Control of Grasping/Guiding-type Docking Mechanism for Nano-satellite

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Abstract

Laboratory for Space Systems researches a grasping/guiding type docking mechanism. The mechanism has a grasping function to fix relative position and attitude between a nano-satellite and the mechanism and a guiding function to dock a nano-satellite. In the paper, a grasping function is explained in detail. The function has a large grasping space to permit control errors of a nano-satellite, grasps it into the space. A grasping control algorithm consists of three routines which check the approach of a nano-satellite and the beginning/end of the grasping. This paper discusses feasibility of the grasping function including practical mechanisms and control algorithms through microgravity experiments.

超小型衛星用把持引込型ドッキング機構の把持制御

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概要

超小型衛星を繰り返し回収・結合・放出する機能を持つ把持引込型ドッキング技術に関連し、試作した機能実証モデルを対象とした把持制御則を提案して、把持機能実証実験を行った。具体的には、ドッキング機構が有する把持空間内で制御誤差を有する超小型衛星を確実に把持することを目的として、把持機能を最小限の構成で実現するための機構・制御システムを構築し、微小重力実験によって衛星に対する制御精度要求を抽出し、その妥当性を評価した。

1. Introduction

In the near future, inspection and measurement missions with nano-satellites have lately attracted attention. For example, XSS-10 nano-satellite by Air Force Research Laboratory inspected the 2nd stage of rocket. But the life time of XSS-10 was only 20 hours because it didn’t have electric power system. The missions with nano-satellites demand recharge and refuel system to extend their life time. The authors proposed a mothership-daughtership satellite system to realize recharge and refuel system for nano-satellite [1, 2]. The system consists of one mothership which is relatively large satellite and some daughterships which are nano-satellites. Mothership takes charge of a base satellite to communicate with daughtership and ground stations and to refuel and recharge daughterships. Daughterships are separated from mothership and conduct variable tasks. And daughterships return and dock to mothership to be recharged and refuelled. Docking technology is important to realize the system. Docking technology has been researched since 1960’s. For example, the Apollo spacecraft docking system is very reliable for manned space flight. This type of docking system is not suitable for autonomous docking system for nano-satellite. 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 NASA (the former organization of JAXA), is an excellent autonomous docking system [3] but the system needs a high accurate onboard control system with many complicated sensors such as rendezvous radars, GPS receivers and proximity sensors. The
unmanned docking of ETS-VII is not suitable too. The reason is that size and weight of nano-satellite are very severe and it is difficult to equip nano-satellite with many sensors and special mechanics. Laboratory for Space Systems (LSS), Tokyo Institute of Technology (Tokyo Tech) studies and develops a new docking methodology for nano-satellites. And we design and assemble a functional test model to conduct verification experiments. It is important and difficult for space engineering researchers to realize microgravity environment at the ground experiments. The research conducts 2-dimensioonal microgravity experiments using flat table in our laboratory and 3-dimensioinal microgravity experiments using a drop shaft at Japan Microgravity Center (JAMIC). In the paper, we explain the grasping/guiding docking methodology and mechanism for nano-satellite. In particular, we discuss the feasibility study of grasping function including a practical control algorithm and a grasping behaviour through two types of microgravity experiments.

2. Development of the Docking System for Nano-satellite

2.1 Docking Methodology

We propose a concept of new docking method available for nano-satellites like mothership-daughtership configuration. Fig. 1 indicates the schematic of the proposed docking methodology. The proposed docking phase is divided into two phases. Phase 1 is an approach/grasping phase. In this phase, the nano-satellite approaches a docking space inside the docking mechanism. The docking space is large enough to permit position and attitude control error of the nano-satellite, and the docking mechanism is able to grasp the nano-satellite 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 nano-satellite to a docking port while adjusting its attitude. The docking mechanism can also separate the nano-satellite with attitude and speed control using the same mechanism of phase 2. The methodology is suitable for nano-satellite docking because the docking system is able to fix relative position and attitude without high control accuracy using complex sensors. And nano-satellite doesn’t need any special mechanisms such as a grapple fixture.

2.2 Docking Mechanism

A docking mechanism is designed and developed to verify the proposed docking methodology by experiments. Requirements and conditions on the design are mentioned below. A docking mechanism is loaded with a small satellite which is assumed to be less than 100kg. The nano-satellite is assumed that the size is about 200mm-diameter and 300mm-height in cylinder shape and weight is less than 10kg. Moreover, it has 3-axis position and attitude control system to conduct on-orbit servicings. The most important requirement is how to realize two phases on the docking mechanism. Two functions are designed to satisfy requirements. One function which realizes the phase 1 is called grasping function. Another function to realize the phase 2 is called guiding function. The mechanism consists of grasping parts (like fingers) in order to grasp the nano-satellite on a concentric circle. Size of the docking space is 270mm diameter and 300mm height. Each grasping part has five rollers in order to guide and separate the nano-satellite. The mechanism can realize to guide the daughtership to the docking port and adjust its attitude. Reference [4] is explained the result of design in detail.

2.3 Functional Test Model

A functional test model of the docking mechanism is developed shown as Fig. 2. The model is not the complete model of the designed mechanism. The model consists of essential parts to verify some functions of the proposed docking system and to confirm whether or not all mechanisms can work well and the implemented
control algorithm is reliable. The model has only three grasping parts in order to conduct the functional experiments. The total size is 430mm-diameter and 420mm-height in cylinder. The total weight is 16.4kg. The power consumption is about 12W (24V). The sensing system for the docking mechanism is also a simple system. It is consists of three open limit sensors and three laser displacement sensors. The laser displacement sensors are used to measure the relative distance between the docking mechanism and the nano-satellite shown in Fig. 2.

3. Grasping Control Algorithm and Grasping Possibility Estimation

3.1 Practical Control Algorithm for Grasping
We consider the practical control algorithms, especially for the grasping function. Fig. 3 indicates a flow chart of the grasping function control algorithm.

The grasping function has three check routines. The docking mechanism automatically grasps the nano-satellite certainly by using three check routines. The first routine is called Approach Check Routine. The routine checks whether a nano-satellite 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 nano-satellite comes into the measuring range of the laser displacement sensors. The second routine is called Current Check Routine. This routine checks whether or not the docking mechanism grasps the nano-satellite firmly using the current value of DC motor to close the grasping parts. The control PC monitors 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 threshold value set previously. The third routine is Attitude Check Routine. This routine confirms whether or not the attitude of the nano-satellite is accurate by the comparison of a diameter of nano-satellite with a docking space after the current check routine of the control algorithm. If the attitude of a grasped nano-satellite is bad, the mechanism avoids grasping the nano-satellite and returns to the initial condition.

![Fig. 2 Functional Test Model](image)

![Fig. 3 Grasping Control Algorithm](image)

3.2 Grasping Possibility Estimation
Docking possibility criteria is estimated to compare experiment results. In case of using the
functional test model, results of phase 1 depend on the relative attitude and position between the docking mechanism and the nano-satellite. Fig. 4 indicates relative position and attitude.

Coordinate \{x, y, z\} is defined. Origin is at the center of the bottom of the docking mechanism. \(z\) axis is perpendicular to the bottom plate. \(x\) and \(y\) axis is defined as Fig. 4. Vector \(r\) is defined the position vector and \(\theta\) is defined the attitude of nano-satellite. \(\theta\) indicates a vertical angle of cone formed by nano-satellite. And the constant value of the model is defined below.

\[\phi_s = 270\text{mm} : \text{Diameter formed by grasping parts}\]
\[h_s = 300\text{mm} : \text{Height of nano-satellite}\]
\[\phi_d = 200\text{mm} : \text{Diameter of nano-satellite}\]
\(\phi_d\) is called “Docking Space”. When position of nano-satellite is \(\mathbf{r} = [x \ y \ z]\), the relation between \(\mathbf{r}\) and \(\theta\) is the following.

\[\theta = \arcsin \left( \frac{\phi_s - 2\sqrt{x^2 + y^2}}{\sqrt{h_s^2 + \phi_s^2}} \right) - \alpha \quad (1)\]

In equation (1), if position error of nano-satellite is 0mm, attitude error tolerate up to 14.5deg. If attitude error is 0deg, position error tolerate up to 35mm. However, equation (1) is available only if grasping parts touch nano-satellite sufficiently. Grey zone in Fig. 5 indicates grasping possibility area called “Complete Grasping Area”. In the area, the docking mechanism grasps nano-satellite reliably by three grasping parts. The estimation results compare to experiment results. Additionally, tolerance of maximum approach speed is 92.6mm/s from another calculation.

4. Microgravity Experiments

We conducted two types of microgravity experiments to verify our docking methodology, mechanism and control algorithm and to analyze the docking dynamics. Each experiment has the different features. Therefore, we need to change objectives, verification points and experimental methods in each experiment.

4.1 2-Dimensional Microgravity Experiments

One is 2-dimensional microgravity experiment using the floating satellite simulators on the flat table developed in our Laboratory [5]. In this experiment, we verify the whole docking methodology and evaluate the mechanism and control method of grasping/guiding function on various approaches of nano-satellite [2,6,7].

We attached the docking mechanism and a nano-satellite model to each simulator. The nano-satellite model is the size of 200mm-diameter and 200mm-height in cylindrical shape and it has gyro sensors, accelerometers, CCD cameras and batteries. The docking mechanism on the simulator and the nano-satellite model is shown as Fig. 6.

The docking sequence is controlled by the command from a remote ground station. The docking mechanism faces the nano-satellite model by the attitude control. The simulator, which has the docking mechanism, stays at the initial position with floating by the air pads and the nano-satellite approaches to the docking mechanism by 54mm/s. Fig. 7 shows one of the experiment results. The pictures indicate the followings; (a) the nano-satellite approach the docking mechanism with a translational speed of about 54mm/s, (b) the nano-satellite comes into the
docking space and the position/attitude control of the nano-satellite is off, (c) when the docking mechanism detects nano-satellite, it starts the close motion to grasp the nano-satellite, (d) the docking mechanism changes control mode from the close motion to the grasp motion, (e) the docking mechanism guides the nano-satellite to the docking port, (f) the docking phase is completed, (g) the start the release motion after received an uplink command from the ground station, (h) the docking mechanism starts the open motion when the nano-satellite removes from the docking space, (i) after releasing the nano-satellite, the experiment is finished. We verified the mechanism and control method on the proposed methodology.

We have conducted 3-dimensional microgravity experiments six times since 2001 and the references [2, 8] explain the experiments in detail. The experiment system for JAMIC is developed shown in Fig. 8. The experiment system consists of the docking mechanism, the nano-satellite model, a release mechanism, support circuits with a laptop PC, CCD cameras and batteries. The release mechanism is made to release the nanosatellite immediately after receiving a drop command signal. The experiment sequence is followings: (1) the experiment system is insert into a JAMIC’s dropping rack, (2) the dropping rack is set up to a drop capsule, (3) the drop command is transmitted to start dropping the rack, (4) the docking sequence is started when the laptop PC receives the drop command, (5) the docking mechanism starts the close motion and the nano-satellite releasing from the release mechanism, (6) the experiment sequence is finished after about 10s. During the experiments, the system works automatically.

Fig. 6 Docking Mechanism on Simulator (Left) and Nano-satellite Model (Right)

Fig. 7 Slides of 2-Dimensional Experiment

4.2 3-Dimensional Microgravity Experiments

Another is a free-fall type microgravity experiment at JAMIC. In the experiments, high quality microgravity environment (about $1.5 \times 10^{-3} G$) is achieved for 10s and we verified the grasping function and analyzed the docking (grasping) behaviour under the microgravity environment.

We will explain the event sequence evaluated from the acquired images shown in Fig. 9.

The events at one experiment are the followings; the capsule starts to drop at 0.00s, 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. An average microgravity level is kept at 1.9e^{-3}g. Approaching conditions are that angular misalignment is about 10deg and linear velocity is about 71.4mm/s calculated from sensor data. These nano-satellite conditions are in the grasping ability. The result indicates that grasping function is effective in the proposed docking methodology for nano-satellite.

![Fig. 9 Slides of JAMIC Experiment](image)

5. Conclusion

The paper explains the propose docking methodology for nano-satellite and development of the functional test model of the docking mechanism based on the methodology. The practical control algorithm for grasping function is explained. Finally, we conduct 2-dimensional and 3-dimensional microgravity experiments to verify the grasping function. The mechanism and control method based on the proposed methodology are feasible for nano-satellite docking system.

As future works, guiding control algorithm is more sophisticated to recover from incomplete grasping. For example, docking mechanism adjusts the grasping torque to make nano-satellite slip. And precise docking criteria are estimated from numerical and experimental data [9].

References


