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論文内容要旨

1 Introduction

Space-stations and artificial-satellites floating in space are light and slender from an ability of the performance of a rocket and cost of its shooting. Generally, space structures have a limitation of the solidity and safety in comparison with arificial structures on the ground. Sun panel as seen on the space-station and artificial-satellite needs large area for getting sun rays, effectively. The characteristics of the structures in space are having light-weight, some flexibility for the solidity, and its shape is extremely slender, long and thin. Maintenance of structures having such a characteristics by human being outside the station is very risky job. That is why many researchers have tried to realize such tasks accomplished by space-robots. Realization of handling of the space-structure by the space-robot equipped on the space-station replacing human being is possible (*e.g.*, a vibration suppression of the sun-panel and a carrying of structures and so on).

Figure 1 shows the situation of the maintenance of the space-structure by a tele-operated type robot in space. The robot is of free-flying type one having the motor for handling the object and TV cameras for observing the motion of the sun-panel. Furthermore, the robot can move by itself (*e.g.*, by jet engine and so on). The robot arm consists of links and two end-effectors at its ends. One end-effector is meant for fixing the robot on the base such as a satellite bus and the other is for handling the object.

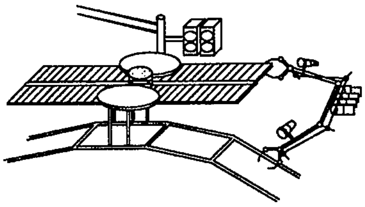

Figure 1: Maintenance of the sun-panel by a free-flying-robot in space.

Next, we explain about the historical background of handling strategy for the object. Some researchers have started the study of control of the flexible object. The study of handling of the flexible object using a single-arm robot has been done. The purpose of that research is to devise the position control strategy for insertion of one end of the flexible bar into a hole in concrete while holding the other end. On the othe hand, also the study of coordinated control of the rigid object using the rigid dual-am robot has been already done. Some researchers have given theoretical derivation of workspace coordinates for the dual-arm robot handling the rigid object. Recently, the study of coordinated control of the flexble object using the rigid dual-arm robot has started. Some researchers have applied the geometrical analysis to perform the position control and vibration suppression of the flexible object. In these researches, the flexible object consists of lumped masses and springs. While in this thesis, we consider the object to be a dynamic flexible beam.

The situation of this thesis has the two types of handling: one is a problem for handling an end of the flexible object by a robot while another end is fixed in the wall, and the other is a problem of a cooperative handling of the flexible object by robots.

2 Modeling of Robot and Object

In this chapter, discrimination of the equation of motion of the robot and the modeling of a flexible object have been mentioned.

For the robot we deal with the equation of motion using Lagrange's formulation. For the modeling of the object we choose the object to be a flexible beam, and formulate the two kinds of modeling: one is a very simple model in 1-D space given by the Galerkin's method, and the other is a model in 2-D space given by using the Simo's method. The model in 2-D space covers a number of flexible objects, from daily life: *e.g.*, bean curds, cakes, as well as spiral wires as shown in Figure 2. For the active handling technique of the flexible object, it is important to constitute the dynamic model of the flexible object.

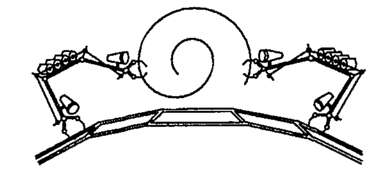

Figure 2: Situation of handling a wire by two robots.

3 Identification of Flexible Object

In this chapter, a method of simultaneous observation, following and identification of a flexible object by a robot before the robot handles the object has been proposed.

First, we distinguish the task of the robot as observation, following, handling, and manipulation of the object (Figure 3). Second, we constitute the control system to make achieve two performances: observation and identification of the object using only one identification method.

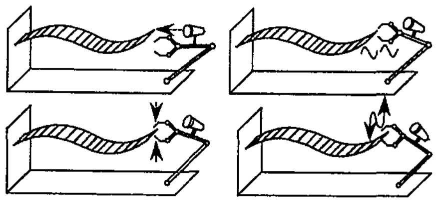

Figure 3: Observation, following, handling, manipulation.

4 Interactive Handling System

In this chapter, an expression of the constrained force/torque in the handling position and a handling method satisfying under-contact and non-contact conditions of the robots with the flexible object have been proposed.

Overview of the proposed model is shown in Figure 4. As the first situation in this thesis, we regard the robot as rigid manipulator and the object as its one side being free and the other side fixed in the wall. The robot and object together have made up a unit system, so that whole system builds up a closed loop. Generally, the analysis of thus constrained dynamical system has been done with the unknown multiplier method. However, we apply a new method to calculate the interaction force in the handling points based on the numerical management which does not demand any consideration of the constraint condition.

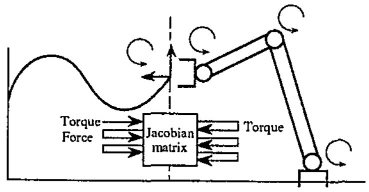

Figure 4: Summary of the combined system.

For developing this method, we also propose a handling method satisfying under-contact and non-contact conditions of the robot with the flexible object.

5 Cooperative Handling System

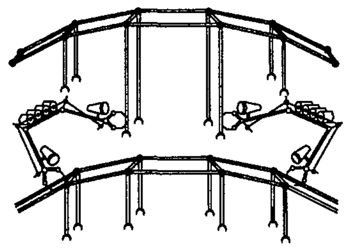

Figure 5: Situation of handling a flexible structure by two space robots.

In this chapter, we deal with the hadling of a free-flying flexible object by robots. As the second situation in this thesis, a method of the constitution of the full assembly system including robots and a flexible object while satisfying the positional boundary conditions at the handling points using the constraint forces, has been proposed. We consider the robots and the object together as the entire system, and make a mathematical model for the combined system. The situation of handling a flexible structure by two space-robots is shown in Figure 5. If the parameters of the object are larger than that of the robots, it is important to consider the cooperactive control for the combined system and make it possible that the micro robots can manipulate the macro object. In particular, in space, it seems that demands for manipulating a large-scale structure by a space robot will be increasing. Therefore, it is important to constitute the cooperative control problem of several robots handling a flexible object, and to analyze the proposed control system.

We also try to examine the stability of the robots when no control input at the reference equilibrium point, is applied to the combined model of the robots and the flexible object.

6 Duality of Handling System

In this chapter, we have considered the relationship between the handling model in Chapter 4 and the model in Chapter 5.

We have understood that the handling model based on the numerical management in Chapter 4 corresponds to the model using the unknown multiplier method in Chapter 5.

7 Controllability of Flexible Object

In this chapter, we have examined the controllability of the flexible object.

We have concluded that each robot needs more than three links, and the controllability condition does not depend on the existence of the end-effector.

8 Cooperative Handling Design

In this chapter, the control design of the handling model in Chapter 5 has been presented.

We have also proposed a discrimination criterion about the stability and the robustness of the control system.

9 Path Planning

In this chapter, a path planning for minimizing the internal forces at the handling points not to vibrate the flexible object, has been observed.

10 Conclusions

In this thesis, handling methods of a flexible object by robots have been explored. We have tried to examine various problems in handling the flexible object by robots.

To realize practical usage of the handling of various large scale structures by space-robots, a lot of researches are to be done.

In future work, we would like to find a limitation of the handling tasks for the flexible object by robots.

審 査 結 果 の 要 旨

宇宙空間では，微小重力環境下にあるため，小型のロボットで大型柔軟構造物のハンドリングが可能であり、これより，柔軟対象物の特性を陽に考慮したハンドリング設計法の開発が求められる。しかし，このような柔軟対象物のハンドリングでは、対象物の内部ポテンシャルの影響により，ロボットが対象物から受ける力は静力学的には決定されない。一方，ロボットが対象物の全て点の位置やポテンシャルの情報を完全に把握することは難しい。しかし、限られた点の位置と把持点での力情報よりハンドリングを実行すると、その際，対象物に振動を励起する可能性がある。本論文は，このような柔軟対象物のハンドリングに関して，モデリング，制御系設計，安定性，ロバスト性など種々の角度より行った研究結果をまとめたもので，全編10章より成る。

第1章は，序論である。

第2章では，本論文で対象とするロボットの動力学および柔軟対象物のモデリングについて述べている。

第3章では，ロボットにより，運動する柔軟対象物の観測，追従，および動特性同定を同時に行う方法を提案している。

第4章では，ロボットと柔軟対象物の間に生じる干渉力を表現するモデルの導出と，その干渉力を求める数値シミュレーションについて述べている。

第5章では，把持点での位置的拘束条件に基づき，ロボットと柔軟対象物の動特性を結合させたモデルの提案を行っている。これは重要な成果である。なお，本章以降では，ロボットとして複腕ロボットを考えている。

第6章では，第4章と第5章で提案した二つのモデルの関係について考察し，両者の等価性を示している。これは重要な知見である。

第7章では，柔軟対象物の可制御性の評価を行っている。

第8章では，第5章で提案した結合モデルについて，制御系の設計を行っている。さらに，制御系の安定性やロバスト性についての基準を導いている。

第9章では，拘束力を小さくし，柔軟対象物の振動を励起させないためのハンドリング軌道計画法を提案している。

第10章は，結論である。

以上要するに本論文は，剛体ロボットによる柔軟対象物のハンドリング法を確立するため，柔軟対象物の動力学モデルを求め，それに対して有用な制御系設計法を提案したものである。この方法により，ロボットに比べ柔軟対象物の動特性が大きい場合について，ハンドリング制御系の設計が可能となる。したがって，本論文はロボット工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。