Control and Grasp for Space Robots with Flexible Components

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論 文 内 容 要 旨

Chapter 1: Introduction

Interest in space robots has increased in recent years, with many space robot systems being planned and in operation for a variety of missions: space debris removal, manned space activity support, planetary exploration, etc. These robotic systems are usually equipped with flexible appendages, such as solar panels and antennae, or are mounted on flexible bases, such as the long lightweight arms on the International Space Station (ISS). These flexible components are dynamically coupled with the rigid parts of the robots, and the resulting vibrations can lead to a decrease in performance. Appropriate motion control strategies considering flexibility are required for secure operation of these space robots. In addition, a robust technique for grasping of various free-flying objects in microgravity is required for such robots.

This thesis describes the dynamics, control strategies, and grasping techniques for space robots with flexible components and robotic arms. Both free-flying robots and tether-based mobile robots are addressed. In addition, a robust robotic hand for grasping free-flying objects is discussed.

Free-flying robots are used for on-orbit serving, such as space debris removal. These robots are equipped with flexible appendages and rigid manipulators that are used for approaching and grasping space debris. The manipulator motion and contact with targets to be grasped can induce vibrations in the flexible appendages. By contrast, the tether-based mobile robot is used on large space structures for various services such as a construction, operation, and maintenance of space facilities including the ISS. These robots are constrained geometrically by several tethers whose anchors are attached to points on the space structures, and can move within the area bounded by the tethers' anchors by changing the tethers' lengths. This bounded area can also be changed in systems where the tether-based mobile robots have extendable and retractable arms for repositioning the anchors. The tethers and the extendable arms have high flexibility, which can induce vibrations in the robots. The vibrations of such space robots due to the components' flexibilities decrease the operation accuracy, increase the risk of mission failure, and wear out the flexible components. In this study, dynamic models and control methods for both the free-flying robots with flexible appendages and the tether-based mobile robots are discussed on the basis of a comprehensive model.

In addition to the dynamics and control methods of the space robots with flexible components, a robotic hand for grasping free-flying objects is presented. These robots are required to be able to perform grasping maneuvers with space debris and astronaut tools. Specifically, high robustness with respect to position errors and target shapes is required for practical application in space. Moreover, a technique to avoid target pushing (pushing/knocking targets away to unrecoverable trajectories) is required for such systems. In this study, a robotic hand satisfying the above requirements is proposed and verified with several analyses and experiments.

Chapter 2: Dynamics of Space Robots

This chapter introduces the dynamics and fundamental theories of space robots for developing control methods. First, the dynamic model and the equation of motion of rigid space robots based on multibody dynamics are reviewed. In addition, a comprehensive dynamic model of space robots with flexible components is proposed using a virtual joint model, which approximates flexible structures as virtual rigid links and passive joints. The equation of motion of the comprehensive model is also derived.

Chapter 3: Dynamics and Control of Free-Flying Robots with Flexible Appendages

This chapter presents the dynamics and control methods of free-flying robots with flexible appendages. Previous research on modeling and control methods for free-flying robots with rigid manipulators and flexible appendages is limited. In this study, a simplified dynamic model based on the comprehensive model to concisely express the flexibility of the appendage is proposed. This model is expressed as a simple articulated body system, and therefore makes it possible to calculate the control input using the limited resources of space robots. On the basis of the proposed model, three control methods are formulated: end-point control, vibration suppression control of the flexible appendage, and simultaneous control, where both methods are integrated. A state estimator for the flexible appendage, which provides necessary feedback for the relevant control methods, is developed using a force/torque sensor attached between the base and the flexible appendage. The proposed control methods were verified experimentally using an air-floating system, which can emulate planar microgravity with frictionless motion. The experimental results prove that proposed methods based on the simple model can increase the accuracy of end-point control and suppress the vibrations of flexible appendages.

Chapter 4: Dynamics and Control of Tether-Based Mobile Robots

This chapter discusses the dynamics and control methods for tether-based mobile robots with extendable arms. Previous studies have not addressed the details of three-dimensional dynamics of such robots in space, which is difficult to evaluate on Earth, but essential for future missions. In this study, therefore, both ground experiments and flight experiments on the ISS were conducted to analyze the three-dimensional dynamics of the extendable arm and the tethered robot. From the analyzed results of the experiments, dynamic models of the extendable arm and the tethered robot are proposed on the basis of the comprehensive model derived in Chapter 2. Parameter values used in the proposed models are identified from the experimental results. In addition, the proposed models were verified by comparing the experimental results and the simulation results obtained using the proposed models. Furthermore, the vibration suppression control of the extendable arm using a manipulator on the arm's tip is proposed. The proposed control method was validated with numerical simulations and experiments using the air-floating system. The above research results provide the details of the three-dimensional dynamics and control methods for improving the tether-based mobile robot's performance.

Chapter 5: Caging Grasp for Free-Flying Objects

This chapter describes the development of a robotic hand for grasping free-flying objects in microgravity. In this study, a robotic hand was designed and developed on the basis of two concepts: underactuation and caging. The underactuated hand employs a simple mechanism and has the capability to adapt the finger configuration automatically to the target shape using elastic elements. Caging is a technique to create a geometrical enclosure around the target without contact. This technique enables the robot to avoid target pushing and to control without accurate positioning. Integrating these techniques makes it possible to grasp free-flying objects reliably in space.

The proposed robotic hand is evaluated by a quasi-static analysis and a geometric analysis based on a condition called object closure. To demonstrate the theoretical discussions, a prototype of the robotic hand was developed and its performance was tested. In the performance tests, caging grasp motion and self-adaptation to target shapes were evaluated. Moreover, experiments of grasping a free-flying object with/without caging were conducted using the air-floating system. The experimental results prove the robustness of the caging grasp. Finally, as an application of the proposed robotic hand, a concept to relax the end-point attitude control for additional tasks is proposed and validated through several simulation case studies. The study achieved the development of a robust robotic hand that performs caging grasp and self-adaptation to target shapes.

Chapter 6: Conclusions

This thesis addressed the dynamics, control strategies, and grasping techniques for space robots with flexible components. First, a comprehensive dynamic model for the space robots considering components' flexibilities is derived using a virtual joint model. This study proves that both free-flying robots with flexible appendages and tether-based mobile robots can be controlled on the basis of the comprehensive model. In addition, an underactuated hand that performs caging grasp was designed and developed for secure grasping of free-flying objects. The control methods and the robotic hand developed in this study reduce the end-point position errors due to the component's flexibility, and enhance robustness for grasping free-flying objects.

論文審査結果の要旨

軌道上のスペースデブリの捕獲・除去や，宇宙ステーションのような大型宇宙構造物の点検・保守などを行うための宇宙ロボットの開発が期待されている。デブリの捕獲・除去には宇宙空間を自由飛行するフリーフライング型ロボットが適していると考えられ，一方，大型構造物の点検・保守には宇宙ステーションの外壁を伸展アームとテザーを用いて移動するテザー移動型ロボットが提案されており，それぞれロボットとしての形態は異なるものの，ロボットアーム制御の観点からは，両者は柔軟構造物を含む宇宙ロボットとして共通の技術課題を内包している。本論文は，柔軟構造物を含む宇宙ロボットにおいて，系全体の柔軟性を考慮したロボットアームの制御法と，確実性の高い対象物の把持機構について包括的に論じたものであり，全編 6 章よりなる。

第 1 章は序論であり，本研究の背景および目的を述べている。

第 2 章では，微小重力環境における宇宙ロボットの動力学の定式化において，構造的に柔軟な要素に対して仮想受動関節モデルを用いた，一般性の高い数学モデルを提示している。仮想受動関節の配置を変更することにより，さまざまな形態の宇宙ロボットを同じ方程式でモデル化できることを明らかにしている。これは重要な知見である。

第 3 章では，太陽電池パドルのような柔軟付属物を有するフリーフライング型ロボットについて，柔軟付属物の振動を抑制しつつ，ロボットアームを制御する手法を導出している。また，空気浮上により平面運動に対して物理的にフリーフライング状態を模擬できるロボット試験装置を開発し，導出した制御法を実験的に検証している。これは有用な成果である。

第 4 章では，テザー移動型ロボットについて，ベースを固定するテザーや伸展アームの振動を抑制しつつ，ロボットアームを制御する手法を導出している。JAXA の宇宙ステーション点検用テザー移動型ロボットの技術実証プロジェクト REX-J に参加し，軌道上におけるテザーや伸展アームの振動力学特性に関するデータを収集するとともに，これらの知見に基づいた具体的な制御法を提案している。これは重要な成果である。

第 5 章では，ロボットアームの先端に取り付けられる把持機構の設計法について論じ，Caging Grasp（先に対象物を囲い込み，その後把持動作を行う捕獲方法）の概念の重要性を指摘し，わずか 1 個のアクチュエータにて Caging Grasp を可能とする 2 本指の把持機構の設計例を示し，試作・評価を行っている。また，Caging Grasp を導入することにより，ロボットアーム先端の位置決め制御に対する制約条件が緩和され，第 2～4 章で論じられている振動抑制との同時制御が容易になることを指摘し，計算機シミュレーションにより 3 次元モデルに対するケーススタディを行い，その有効性を検証している。これは，重要かつ有益な成果である。

第 6 章は結論である。

以上要するに本論文は，柔軟構造物を含む宇宙ロボットにおいて，柔軟物の振動を抑制しつつロボットアームを制御し対象物を確実に囲い込み把持するという課題に対し，ロボットシステムの形態や関節配置に関わらず包括的に取り扱うことのできる方法論を示し，その有効性を，地上実験，軌道上実験，および数値シミュレーションを用いて検証したものであり，航空宇宙工学および宇宙ロボティクス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。