衛星捕獲作業中における宇宙用マニピュレータのダイナミクスと制御

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論文内容要旨

Free-flying manipulator systems are envisioned to perform servicing, inspection and assembling operations in orbit. The control of such systems is a challenging task, since the equations that govern their motion are highly nonlinear. Furthermore, unlike fixed-base manipulators a free-floating robot exhibits nonholonomic behavior as a result of the nonintegrability of the angular momentum conservation law.

Much effort has already been dedicated to free-flying and free-floating systems from the viewpoint of inertia coupling effects between the manipulator and base motion. In many cases such coupling effects are beneficial (base vibration suppression control using the manipulator system), in others they impose great difficulties for the control algorithms (applications related to reactionless motion planning). Extensive analysis of this phenomenon is necessary since it can extend the capabilities of space manipulators. In this thesis, different problems typically appearing as a result of the above mentioned dynamic coupling effects are discussed.

The work is divided into six parts. Chapter 1 is introductory and outlines some of the typically appearing difficulties during the utilization of free-flying and free-floating systems. Its is organized as a short literature survey that makes an overview of some of the dynamic modeling, planning and control strategies introduced up to now.

Chapter 2 develops the dynamic equations governing the motion of a general manipulator system with open or closed-loop structure that is mounted on a free-floating base. The formulation presented is used as a framework for the

remaining chapters of this thesis.

Chapter 3 makes an outline of some of the fundamental concepts and strategies used for the control of free-floating systems. It is intended to be a review of some of the existing methods, closely related to the problems studied in this thesis.

The main topic addressed in this study is the capture of a tumbling satellite using a robotic manipulator. In resent years, such operation has been recognized to be a priority task, since its solution is expected to be applied to a variety of space missions, involving servicing, inspection, and repairing operations. The approaching motion of a manipulator arm to a target satellite and the resulting post-impact motion of the system are discussed in Chapters 4 and 5, respectively. The aims of the analysis made can be outlined as follows;

(1) to provide further insight into the problems occurring while capturing a tumbling satellite;
(2) to propose a new method for planning a reactionless end-effector paths to a desired point in Cartesian space;
(3) to propose a strategy using bias angular momentum that can facilitate the trajectory planning and post-impact control;
(4) to propose two control laws for the post-impact phase that can manage the momentum in the system in a desired way.

Chapter 4 deals with the approaching phase of a satellite capturing operation. The first three sections introduce the problems that need to be solved, the assumptions upon which the study is made, and a generalization of the coupling angular momentum concept. This generalization is stated as a theorem, referred to as the coupling wrench theorem. It establishes a clear condition which if satisfied, the stationary state of the spacecraft base will be maintained in the presence of external forces/torques. This condition proves to be useful for the formulation of "favorable angular momentum distributions", which if obtained during the manipulator approaching motion, lead to certain advantages from the viewpoint of base attitude control during the post-impact phase.

Section 4.4 deals with the problem of designing a reactionless path for a n DOF manipulator to a point in Cartesian space. Although the discussion is made from the viewpoint of stationary satellite capturing operation, the solution to such problem can have many practical applications. The concept of Holonomic Distribution Control (HDC) is introduced. It is pointed out that if the manipulator is controlled using HDC, simplifications to the path planning problem can be achieved. The newly introduced control is partially based on a strategy previously employed for solving the inverse kinematics problem for a redundant manipulator arm by partitioning the Jacobian matrix into full rank minors. In short, the main idea is to partition the manipulator joint variables into different sets. Each of these sets, referred to as *primitives*, has a *degree* of redundancy "one" with respect to the base attitude motion (one dimensional distribution in joint space is used). It is pointed out that by choosing different primitives to be used during different stages of the manipulator motion the planning process can be simplified significantly. The planning problem that needs to be solved when holonomic distribution control is employed is a typical nonlinear mixed-variables optimization problem. In order to find solution, a mesh adaptive direct search algorithm is used.

Up to now, utilization of manipulator pre-impact configuration for minimizing the base reactions, as a result of a force impulse applied at the end-effector, have been discussed by a number of researchers. In the case when a force impulse (with known direction) is applied for an infinitesimally small time period, the above approach can yield satisfactory results. However, in the case of a continuous contact with a tumbling target satellite, where the magnitude and direction of the forces has to be assumed unknown, obtaining a pre-impact manipulator configuration is not advantageous. Section 4.5 deals with a tumbling target satellite capturing operation, where the idea of the bias momentum approach (BMA) is introduced. It is based on obtaining a favorable angular momentum distribution in the chaser satellite before the contact with the target object. Advantages resulting from the application of this new approach are discussed. In addition, notes on its practical implementation are made. The problem of trajectory planning for the end-effector to a grasping point, positioned on the target satellite (when BMA is applied) is addressed. It should be noted that, for a general 3D manipulator system, trajectory planning for such case, is still a challenge for the research community. We utilize a two step method based on the utilization of numerical optimization techniques, which led us to satisfactory results in most of the cases studied. A discussion on the influence of the state variables utilized for the optimization procedure, on the algorithm convergence rate is made in Section 4.5.3. A numerical simulation using a seven DOF manipulator is performed in order to verify the presented control strategy.

The main contributions of Chapter 4 are: (i) introduction of the Holonomic Distribution Control, which can be utilized for reactionless path planning to a stationary target satellite; (ii) the introduction of the Bias Momentum Approach, methods for its application and discussion on its influence on the post-impact motion of the system.

Chapter 5 is dedicated to the post-impact phase of a capturing operation. Analysis of manipulator motions that result in maintaining the stationary state of the spacecraft's base in the presence of external forces is made, for this purpose we make use of the newly formulated coupling wrench theorem in Chapter 4. The concept of distributed momentum control (DMC) is introduced and compared with existing post-impact control strategies. A new form of the reaction null space control (RNSC) (which is a well known post-impact control) is presented. In Section 5.3.1 a comparison between a strategy that makes use of manipulator post-impact control, and one that relies on gas/jet thrusters is made. It is shown that the utilization of powerful attitude devices does not necessarily lead to achieving best performance from the viewpoint of fuel consumption. Furthermore, it is pointed out that the distributed momentum control does not use information about the mass and inertia characteristics of the target satellite. Hence, from practical point of view its implementation is straightforward. The merit and validity of both distributed momentum control and reaction null space control are verified by numerical simulations. It pointed out that although joint velocity minimization in the case of DMC, is performed only locally using the pseudoinverse solution, the resultant joint velocity rates have smaller magnitude as compared to the case when RNSC is applied.

The final chapter consists of conclusions and remarks for possible future work.

The utilization of the three new concepts introduced in this thesis;

(1) Holonomic Distribution Control;
(2) Bias Momentum Approach;
(3) Distributed Momentum Control,

can be beneficial for the solution of variety of practical problems. In each section, notes on the practical implementation of those concepts are made. In addition, numerical simulations are performed in order to verify and demonstrate their usefulness.

論文審査結果の要旨

軌道上を自由飛行するいわゆるフリーフライングロボットによる故障衛星の捕獲作業は，ミッション終了後の人工衛星が宇宙ゴミとなることを防止する効果的な手段として期待されている．宇宙ロボットによる軌道上衛星捕獲に関する基本的な技術は，わが国の技術試験衛星 VII 型ミッションにより実証されているが，特に捕獲対象物が回転運動をしている場合については，解決されなければならない課題が数多く残されている．本論文は，宇宙ロボットによって回転する衛星を捕獲する作業を想定し，捕獲に至るためのロボットアーム手先軌道を計画する方法，および捕獲完了後に運動を収束させる方法について，システム全体の運動量配分に注目した新しい概念に基づいて論じたものであり，全編6章より構成される．

第1章は序論であり，本研究の背景と目的について述べている．

第2章では，研究対象とするフリーフライング型宇宙ロボットを多節剛体リンク系としてモデル化し，その運動学および動力学方程式の導出について詳細に論じている．

第3章では，フリーフライング型宇宙ロボットに特徴的な制御手法として，ロボット本体に姿勢変動を生じないための無反動制御法について論じている．無反動制御を実現するために必要なロボットの自由度数を明らかにし，冗長性を利用して本体姿勢維持と手先軌道追従の両者を満たす運動を，タスクプライオリティーの考え方に基づいて導出している．また現実の制御演算において発生する算術的特異点についても論じている．

第4章では，フリーフライング型宇宙ロボットに搭載されたマニピュレータアームを捕獲対象へ接近させる方法について，以下の三つの新しい手法を開発している．まず第一に，一般に非ホロノーム系であるフリーフライング型宇宙ロボットは，独立な能動自由度が1つのみである場合にはホロノーム系となることに着目し，瞬時的にホロノーム系となるように自由度を縮退させて手先を捕獲対象物に接近させる制御法を開発し，その有用性を数値シミュレーションによって示している．第二に，回転運動し角運動量を持つ対象物を円滑に捕獲するため，捕獲の前にロボットアームにあらかじめ対象物と符号が反対で絶対値の等しい角運動量を与えるバイアスモーメンタム法を考案し，その有用性を数値シミュレーションによって示している．第三に，与えられた時刻に与えられた地点において与えられたバイアス角運動量を実現するためのマニピュレータの軌道計画法を開発し，その有用性を数値シミュレーションによって示している．これら3つの手法は，独創的かつ重要な成果である．

第5章では，対象物捕獲後の制御手法として，第4章で述べたバイアスモーメンタム法に基づいて，捕獲された回転対象物の運動を，ロボット本体の姿勢を変えずに速やかに静止させるためのマニピュレータ制御法について論じている．この際，角運動量分布を記述する速度関係式を用いることで容易に制御が行えることを示し，この手法を分布運動量制御法と名づけ，その有用性を数値シミュレーションによって示している．これは，独創的かつ重要な成果である．

第6章では，結論を述べている．

以上要するに，本論文では，宇宙ロボットによって回転する衛星を捕獲する作業を想定し，(1)捕獲に至るためのロボットアーム手先軌道を計画し制御する方法として，非ホロノーム系を瞬時ホロノーム系に縮退させる方法を提唱し，(2)捕獲時にロボット本体の姿勢変動を最小にするために，あらかじめロボットハンドに運動量を与えておくバイアスモーメンタム法を提唱し，(3)捕獲完了後に運動を収束させる方法として分布運動量制御法を開発し，これら一連の手法の有用性を明らかにしている．この成果は，航空宇宙工学および宇宙探査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．