Control of Flexible Manipulator End-Point and Vibration Using an End-Effector Camera

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論文内容要旨

Chapter 1. Introduction

The researches on flexible robots are originated from the problems of controlling actuated flexible structures. Its practical background mainly comes from the demands from space applications. Most of the robot manipulators used in space are designed to be light, slender, and to have a long reach. The lightweight design of space manipulators presents some challenging technical problems. Due to the lack of stiffness in arm, vibration will be excited during a general maneuver. The low frequency, undesired and uncontrolled vibrations are likely to degrade the accuracy of the system, increase task times, reduce system safety and make the overall control of the system more difficult. In this dissertation, the difficulty of controlling a flexible manipulator is solved through a vision-based approach, which is characterized by the usage of wrist cameras. In this compositive solution, the topics which are considered include an implementation of visual servo employing interpolated images, a vision-based vibration suppression control and the integration of active force control into visual servo.

Chapter 2. End-effector Trajectory Control with Vision

In this chapter, an approach to integrating visual servo into a 3D flexible manipulator is described. This approach adopts the concept from singular perturbation theory. According to this theory, the controller for the overall system can be implemented simply as the summation of the control inputs for two subsystems: the slow subsystem and the fast subsystem. In this thesis, the overall system controller designed in this way is represented as the summation of a visual servo designed for rigid motion regulation and a vibration suppression strategy

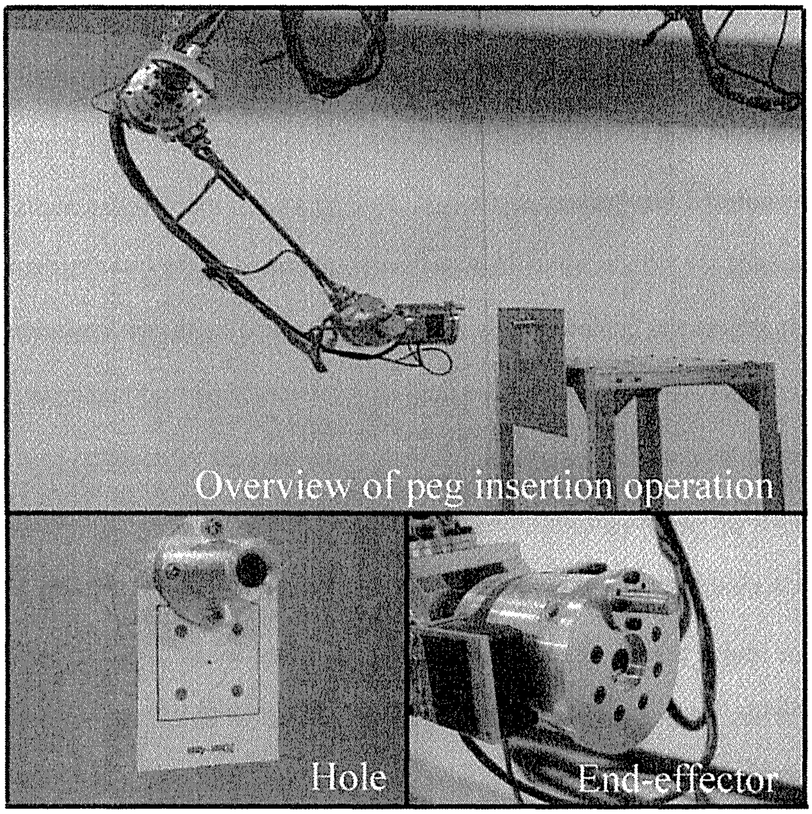

Fig. 1 Overview of an experiment.

designed for elastic motion control. Different from the general way of applying singular perturbation theory, the implementation in this thesis is characterized by the usage of a set of filters. It makes the isolation between the slow subsystem and the fast system possible, considering their difference in frequency domain. This approach is proved to be a simple and effective solution. An analysis to the overall system stability including vibration is given in this chapter. The scheme is also verified through a practical application. In this chapter, a peg-in-hole experiment shown as Fig.1 is carried out to demonstrate the effectiveness of the proposed approach. Its result is described in this chapter.

Chapter 3. Integration of Force Control in Visual Servoing

The contents in this chapter are concentrated on the issues about force control implemented in flexible manipulators. The first topic described is concerned with the problem of integrating active force control into the visual servo proposed in the last chapter. Since during the peg-in-hole experiments described in the last chapter, it indicates that the mechanical compliance involved within flexible links is sometimes not adequate to ensure success of a precise operation. During the attempts to complete the insertion employing parts with smaller clearance, insertions failed. In this case, the introduction of active force control is proved to be a solution. The additional force control is integrated into the visual servo under the framework of impedance control. This kind of integration does not necessitate the precise knowledge about the constraint conditions. However under this control scheme, the DOFs controlled by vision and that controlled by force are not distinctly isolated. The problem resulted from this property is revealed in experiments and a discussion about it is also provided in this chapter. The second topic of this chapter is concerned with implementing a compliance operation mode through utilizing the information from strain gauges. In this approach, the necessary force information used in a standard impedance control is obtained from the strain gauges. The implemented compliance operation mode is used to force the arms into a precisely designed calibration tool to adjust arms' initial position.

Chapter 4. Trajectory Control Using Interpolated Image Sequences

In this chapter, image interpolation techniques are introduced to the visual servo proposed in the last chapter to make the approach capable of specifying tip trajectory. Its necessity is firstly demonstrated by the vision-guided peg-in-hole experiment incorporating two cooperative arms. During the dual-arm version of parting mating, it is found that the main reason of the misalignment between the two arms is the infeasible trajectory generated by the visual servo. It reveals one lack of the visual servo used in the previous chapters. And a discussion about the problem is provided. It answers the question of what we can earn from applying visual servoing for a flexible manipulator.

We argument that the advantage of applying visual servoing techniques in flexible manipulators lies in the possibility of compensating the kinematics errors due to links' bending. This merit is only reasonable when image based visual servoing techniques are adopted, just as the experimental results in the previous chapters have shown to us. An implementation of other kinds of visual servoing techniques in flexible manipulators is not helpful to compensate link's kinematics error but be likely to make the control unstable.

However by using image-based visual servoing, it is difficult to specify end-effector's trajectory. It explains the failures when a dual-arm version of parts mating is attempted. This lack restricts the application of the visual servo in flexible manipulators. The solution to the problem is achieved by introducing the image interpolation techniques. In this approach, the feature points indicating the target position are replaced by the feature points within an image sequence. Thus the specification of the tip trajectory can be done through specifying an image sequence taken by the wrist camera when the tip follows a fine motion. The interpolation between the images within the image sequence generates the reference trajectory for visual servo. This approach can reserve the merit provided by image-based visual servoing and at the same time capable of trajectory planning. Then this method is used to resolve the problem confronted in the cooperative version of vision-guided parts mating. We argument that it is the introduction of image interpolation technique that makes a vision guided flexible manipulator adequate for a practical application.

Chapter 5. Vibration Control with Vision

So far most of vibration control strategies proposed assume that vibration of links or joints can be directly measured by sensors such as strain gauges or accelerometers. However the employment of strain gauge does not imply the best performance in many situations. Present space manipulators do not have such sensors mounted. A strain gauge is apt to be affected by very high noise due to electromagnetic interference. Therefore a vision-based vibration estimation approach is proposed in this chapter. This scheme can be regarded as an extension of the trajectory regulating methods proposed in the previous chapters and actually they are highly complementary. The previous chapters deal with how to use camera in slow subsystem and this chapter considers the possibility of using camera to damp vibration, which is concerned with the fast subsystem. The estimation to link's vibration is achieved by an observer based on Kalman filter. By using it, it become possible to obtain the state of links' deflection without employment of strain gauge sensors. Additionally some technique problems accompanied with incorporating visual information for vibration damping are solved in this chapter. They consist of the solution to the problems due to time delay and a modified Kalam filter corresponding to vision system's slow acquisition speed. With the vibration well estimated using the approach and combined with the visual servo implemented in slow subsystem, it is possible for a positioning control scheme only incorporating camera. This chapter explores this possibility. In the later experiments, the image interpolation based visual servo is combined to the vision-based vibration damping control. The experiments are characterized by the property that both the vibration damping control and the trajectory control depend only on the visual information. The success of the experiment proves the effectiveness of the proposal.

Chapter 6. Conclusions

In this chapter, the concluding remarks drawn out from this study are presented. The main contributions of this thesis consist of the integration of visual servoing into a 3D flexible manipulator, the proposal of a vision-based vibration suppression control and the integration of force control aiming for practical parts mating experiments. These components are highly complementary. The visual servoing and force control are responsible for the task level control and the vision-based vibration suppression control is responsible for regulation of the vibration. The combination of them makes a positioning control strategy only incorporating wrist cameras to be possible. From practical point of view, since on space manipulators, there are no strain gauges attached, the control strategy proposed in this thesis throws a new light on the complex positioning control problem.

論文審査結果の要旨

フレキシブルマニピュレータは，軽量であること，環境との接触時の衝撃力が緩和されることなど，多くの利点を持ち，これについて，これまで数多くの研究がなされてきた。しかし，多くの研究では，弾性リンクの振動を検出するためにひずみゲージを用い，手先位置を検出するために外部にカメラを設置するなど，ひずみゲージや外部カメラを持たない一般のロボットマニピュレータに適用することは想定されていない。これに対して，本論文は，手先カメラからの画像情報を利用し，手先軌道追従制御及び振動抑制制御を行う新しい手法を提案し，7自由度双腕フレキシブルマニピュレータを用いた実験により，その手法の有効性を検証したもので，全編6章よりなる。

第1章は序論であり，本研究の背景及び目的を述べている。

第2章では，手先カメラを用いたビジュアルサーボをフレキシブルマニピュレータに適用する手法を提案し，実験でその有効性を確認している。この手法では，特異摂動法の考え方に基づき，高周波領域で振動制御を，低周波領域でビジュアルサーボ制御を行う。これは簡潔，明快な考え方で，フレキシブルマニピュレータにビジュアルサーボを適用するときの有力な手法である。

第3章では，フレキシブルマニピュレータの手先が環境に拘束されるような作業に対し，第2章で提案したビジュアルサーボに，力制御を組み合わせる手法を提案している。この手法は，フレキシブルマニピュレータに，環境に拘束される精密作業を行わせるとき，有効である。

第4章では，最終目標点の特徴画像から，途中経由点の特徴画像を自動生成し，ビジュアルサーボを用いて，この経路点を通る軌道に手先を追従させる手法を提案している。この手法を用いることにより，途中に障害物があるような場合でも，それを回避する軌道を生成することができる。

第5章では，手先カメラの画像情報のみを用いて，リンクの振動を推定し，抑制する制御法を提案している。この手法により，ひずみゲージや加速度センサを備えていない宇宙ロボットマニピュレータや一般の産業用ロボットマニピュレータに対して，振動抑制制御を行うことが可能となる。この手法は高く評価される。

第6章は結論である。

以上要するに本論文は，手先カメラの画像情報を用いて，フレキシブルマニピュレータの手先軌道制御及び振動抑制制御を行う手法を提案し，精密作業実験を行い，その有効性を確認したものである。本手法は，画像情報のみで制御則を構築できるため，宇宙ロボットマニピュレータに限らず，多くのロボットマニピュレータに適用可能な手法で，その汎用性を考慮すると，本論文は，ロボット工学，機械工学，及び宇宙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。