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R.V. Patel · F. Shadpey

Control of Redundant Robot Manipulators

Theory and Experiments

With 94 Figures

Springer

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To Roshni and Krishna (RVP)

To Lida, Rouzbeh and Avesta (FS)

Preface

This monograph is concerned with the position and force control of redundant robot manipulators from both theoretical and experimental points of view. Although position and force control of robot manipulators has been an area of research interest for over three decades, most of the work done to date has been for non-redundant manipulators. Moreover, while both position control and force control problems have received considerable attention, the techniques for position control are significantly more advanced and more successful than those for force control. There are several reasons for this: First, the effectiveness and reliability of force control depends on good models of the environment stiffness. Second, for stability, servo rates much higher than for position control are needed, especially for contact with stiff environments. Third, techniques that are based on tracking a desired force at the end-effector generally use Cartesian control schemes that are computationally much more intensive and prone to instability in the neighborhood of workspace singularities. The fourth factor is the significantly higher noise that is present in force and torque sensors than in position sensors. While most commercial force sensors are supplied with appropriate filters, the delay introduced by the filters can also affect the accuracy and stability of force control schemes.

A large number of techniques have been developed and used for position control such as Proportion-Derivative (PD) or Proprotional-Integral-Derivative (PID) control, model-based control, e.g., inverse dynamics or computed torque control, adaptive control, robust control, etc. Most of these provide closed-loop stability and good tracking performance subject to various constraints. Several of them can also be shown to have varying degrees of robustness depending on the extent of the effect of unmodeled dynamics or dynamic or kinematic uncertainties.

For force or complaint motion control, there are essentially two main approaches: impedance control and hybrid control. Most techniques currently available are based on one or other of these approaches or a combination of the two, e.g., hybrid-impedance control. Impedance control does not directly control the force of contact but instead attempts to adjust the manipulator's impedance (modeled as a mass-spring-damper system) by appropriate control schemes. For pure position control, the manipulator is required to have high stiffness and for contact with a stiff environment, the manipulator’s stiffness needs to be low. Hybrid control is based on the decomposition of the control problem into two: one for the position-controlled subspace and the other for the force-controlled subspace. Hybrid control works well when the two subspaces are orthgonal to each other. This decomposition is possible in many practical applications. However, if the two subspaces are not orthogonal, then contradictory position and force control requirements in a particular direction may make the closed-loop system unstable.

From the point of view of experimental results, there have been numerous papers where various position and, to a lesser extent, force control schemes have been implemented for industrial as well as research manipulators. There have also been a number of attempts made to extend position and force control schemes for non-redundant manipulators to redundant manipulators. These extensions are by no means trivial. The main problem has been to incorporate redundancy resolution within the control scheme to exploit the extra degree(s) of freedom to meet some secondary task requirement(s). With the exception of a couple of papers, these secondary tasks have been postion based rather than force based. One of the key issues is to formulate redundancy resolution to address singularity avoidance while satisfying primary as well as secondary tasks. A number of redundancy resolution schemes are available which resolve redundancy at the velocity or acceleration level. In order to formulate a secondary task involving force control, it is necessary to resolve redundancy at the acceleration level. However, this leads to the problem that undesirable or unstable motions can arise due to self motion when the manipulator’s joint velocities are not included in redundancy resolution.

While considerable work has been done on force and position control of non-redundant manipulators, the situation for redundant manipulators is very different. This is probably because of the fact that there are very few redundant manipulators available commercially and hardly any are used in industry. The complexity of redundancy resolution and manipulator dynamics for a manipulator with seven or more degrees of freedom (DOF) also makes the control problem much more difficult, especially from the point of view of experimental implementation. Most of the experimental work done to illustrate algorithms for force and position control of redundant manipulators has been based on planar 3-DOF manipulators. The notable exceptions to this have been the work done at the Jet Propulsion Laboratory using the 7-DOF Robotics Research Arm and the work presented in this monograph which uses an experimental 7-DOF isotropic manipulator called REDIESTRO.

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Contents