Advances in Robotic Systems

Part 2 of 2

CONTROL AND DYNAMIC SYSTEMS

ADVANCES IN THEORY AND APPLICATIONS

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PREFACE

Research and development in robotic systems has been an area of interest for decades. However, because of increasingly powerful advances in technology, the activity in robotic systems has increased significantly over the past decade. Major centers of research and development in robotic systems were established on the international scene, and these became focal points for the brilliant research efforts of many academicians and industrial professionals. As a result, this is a particularly appropriate time to treat the issue of robotic systems in this international series. Thus this volume and Volume 39 in this series are devoted to the timely theme of "Advances in Robotic Systems Dynamics and Control."

The first contribution to this volume, "Kinesthetic Feedback Techniques in Teleoperated Systems," by Blake Hannaford, is a particularly appropriate contribution with which to begin this second volume of this two volume sequence. As noted in this contribution, telemanipulation systems span an astonishing scale of ten orders of magnitude. As a result, in earlier times telemanipulation systems were designed to overcome barriers of distance between the operator and the manipulated object. However, recently teleoperation developments are aimed at overcoming the barriers of large differences of scale between the human operator and the manipulated object. Thus, teleoperated systems today span the scale from remote surgery to the Space Shuttle Remote Manipulation System (RMS) for satellite repair and other missions.

The next contribution, "Parallel Algorithms and Fault-Tolerant Reconfigurable Architecture for Robot Kinematics and Dynamics Computations," by C.S.G. Lee and C.T. Lin, presents powerful and robust computational techniques and architectures for the control of robot manipulators. The necessary goal is the development of algorithms of lower computational structures. In particular, the ultimate goal is the achievement of an order-of-magnitude and/or an order-of-complexity improvement in computational efficiency in robotics computations, in general, by taking advantage of parallelism, pipelining, and architectures, while at the same time maintaining efficiency and flexibility in the capability to solve robotic computational problems on the same architecture. In order to design a global architecture for a set of parallel robotic algorithms, the characteristics of these algorithms are identified according to six fundamental features. With the parallel robotics algorithms and a parallel computer architecture, a systematic mapping procedure to schedule the subtasks of the parallel algorithms onto the parallel architecture is presented. Because of the central importance to robotics of the issues presented in this contribution, it constitutes an essential element of these companion volumes on robotics.

The development of autonomous controllers, in general, and "intelligent" robots, in particular, has led to active research in "motion planning." The planning problem has been interpreted and solved in various ways by different researchers. It seems that many times planners completely ignore the dynamics of the system. This has led to the current trend of dividing the problem into smaller subproblems and solving each one separately. The three typical subproblems may be identified as task planning, trajectory planning, and trajectory tracking or motion control. The next contribution, "Trajectory Planning for Robot Control: A Control Systems Perspective," by Sunil K. Singh, provides an in-depth treatment of the central issues noted above, and as such is also an essential element of these companion volumes.

Among the modes of robotics control is adaptive control. The next contribution, "Simplified Techniques for Adaptive Control of Robotic Systems," by Izhak Bar-Kana and Allon Guez, which presents techniques in this area, is an important element of these companion volumes. In particular, in adaptive control techniques it is usually the case that such prior knowledge and conditions as the order of plant or system, the relative degree, inverse stability, stationarity, and external excitation are needed. In this contribution, rather powerful techniques for simple and robust adaptive controllers for nonlinear systems with unknown parameters with particular application for robot manipulators are presented.

The remarkable dexterity and versatility that the human arm exhibits in performing various tasks can be attributed largely to the kinematic redundance of the arm, which provides the capability of reconfiguring the arm without affecting the hand position. A robotic manipulator is called (kinematically) "redundant" if it possesses more degrees of freedom than necessary for performing various specific tasks. The next contribution, "Theory and Applications of Configuration Control for Redundant Manipulators," by Homayoun Seraji, is a rather comprehensive treatment of techniques in this broad area. Furthermore, control techniques for this complex problem area are presented which offer the possibility of efficient real-time control redundant manipulators.

The motions of robotic manipulators are either constrained or unconstrained while they perform tasks. For example, many robotic applications, such as assembly tasks, require constrained motion of manipulators. Two generic cases of constrained motion can be considered: (1) a single manipulator constrained by the environment and (2) multiple manipulators constrained with each other as well as constrained by the environment. The next contribution, "Nonlinear Feedback for Force Control of Robot Manipulators," by Xiaoping Yun, presents an in-depth treatment of issues and techniques in this major area of robotics. Numerous important results are presented. Not the least of these is that by the utilization of nonlinear feedback the simultaneous motion and force control of a constrained manipulator or two cooperative manipulators is converted into the design problem of decoupled linear subsystems, and this is a major result from an applied point of view.

A major challenge in effectively realizing advanced control schemes for robotic systems is the difficulty of implementing the kinematic and dynamic equations required for coordination and control in real time. While the total number of computations appears to be somewhat fewer than that of many scientific computations, implementations in real time imply that these computations must be repeated at high repetitive rates per second. This, then, results in an important computational problem in robotics control. It is these computational aspects of dynamic control techniques in robotics that are the main thrust of the next contribution, "Systolic Architectures for Dynamic Control of Manipulators," by Masoud Amin-Javaheri. The concepts, approach, and techniques presented in this chapter are general enough to be applied to a wide range of robotics control problems and their computational requirements.

In the next two contributions "Techniques for Parallel Computation of Mechanical Manipulator Dynamics Part I: Inverse Dynamics" and "Part II: Forward Dynamics," by Amir Fijany and Antal K. Bejczy, an in-depth treatment is presented for the solution of model-based control techniques in robotic systems, both for inverse dynamics (Part I) and for forward dynamics (Part II). Powerfully effective algorithms and systems architectures are developed and presented. The essential importance of these problems in robotic systems will make these two unique contributions a valuable source reference for workers in the field for years to come.

This volume is a particularly appropriate one as the second of a companion set of two volumes on advances in robotic systems dynamics and control. The authors are all to be commended for their splendid contributions, which will provide a significant reference source for workers on the international scene for years to come.

CONTENTS

KINESTHETIC FEEDBACK TECHNIQUES IN TELEOPERATED SYSTEMS

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I: INTRODUCTION: OVERVIEW OF TELEOPERATION

Teleoperation, the ability to perform physical manipulations of objects from a distant control point, is the newest "tele" technology (coming after telegraphy, telephony, and television). Teleoperation was first reduced to practice by Goertz in the late 1940's.[1] Even at that time it was recognized that controlling the "slave" (remote) robot to track the position and orientation of a "master" manipulator held in the operator's hand was insufficient to effectively perform remote tasks. An essential feature of useful systems was the feedback* of force information to the operator arising from the interaction between the slave and its environment. The essential quality for effective remote manipulation is the replication of both force and incremental motion at the master and slave end effectors. A feedback system implementing this behavior is said to be "Kinesthetic". Kinesthesia is defined as

"The sensation of movement or strain in muscles, tendons, and joints."**

Thus, the effectiveness of kinesthetic remote manipulation comes from its ability to reproduce in the human nervous system the same kinesthetic sensations

*Designation of position as the forward command and force as the feedback variable is arbitrary as explained below. For the purposes of an initially descriptive common vocabulary, a reference system will be described having this configuration and in which the word force is used to indicate both force and torque, and position to indicate position and orientation.
** The Random House Dictionary, Random House, New York, 1978

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as would arise in directly manipulating an object.

The assessment of the quality or fidelity of remote kinesthesia is a major topic in its own right, beyond the scope of this chapter. Numerous studies have highlighted performance measurement methods and results[2,3,4,5,6,7,8]

The first kinesthetic remote manipulation systems, described above, consisted of identical master and slave manipulators. The master was different from the slave only in its base location, and in the attachment of a handgrip to the master at a point corresponding to the center of the slave gripper opening. The control systems for these "joint-based" teleoperators are designed to make sure that the joint angles of the master and slave manipulators correspond, and that their torques are opposed. Because of the identical kinematics, this control law ensures tracking between master and slave and feedback of slave contact force to the handgrip. The control systems for each joint are independent except for position dependent disturbance torques. Correctly coupling the feedback force to the contact force and the slave motion to the master motion defines kinesthetic correspondence between master and slave. The basic control architecture which derives the torques based on the position difference between the joints is referred to as the "classical master-slave teleoperator."

Constraining the master and slave systems to be identical can be costly. For example, if the work volume required to perform the task is much larger than the comfortable range of human manipulation, an unwieldy master is required. Ideally, the master should be kinematically optimized to the human operator and the slave to the task.[9] Teleoperators having dissimilar master and slave are said to posses "generalized teleoperation."[10] Generalized teleoperation requires that master joint motions be resolved in real time to some general representation (through forward kinematics of the master), and in turn that slave motions be resolved from the general representation (such as incremental motion vectors or frames) to joint increments (through the inverse kinematics or Jacobian models of the slave). The flexibility of modern computer systems used for these coordinate transforms means that alternate control modes can be implemented for testing and optimal task performance. In a recently implemented system,[11] one of ten distinct control and feedback modes can be independently selected for each task space axis. These options include for example position vs. rate control, force feedback or no force feedback, and complaint control of slave motion. The resulting number of possible combinations for the whole six axis system is thus equal to one million modes!.

No theory yet exists which can derive the optimal mode to use for a given task, we can only explore small regions of "mode space" with analysis and experiments. Even higher dimensionality results if we consider variations of continuous parameters such as gains and scales.

This chapter will consider a small slice of this rich space of possible teleoperation modes. First we will focus primarily on the effects of variations in two key parameters, the force scale and position scale, then we will describe two-port network models of the performance and dynamics kinesthetic remote manipulation systems.

I-1: Application domains

Although originally developed for handling dangerous materials in the nuclear industry from a distance, teleoperation is now a generic technology which can be applied to a wide variety of problems. Most of them still involve separation of the human operator from an inherently dangerous manipulation task.

In describing kinesthetic remote manipulation, we have referred to force (also refered to as "effort") as the feedback variable, and position ("flow") as the forward command. This way of thinking can be a convenient approach for system design. Such a design can be described as a "forward flow" design because the flow variable is transmitted from master to slave (and the effort variable is fed back). The essential quality for kinesthesia is that the efforts and flows at the handgrip and slave gripper closely correspond. Although the forward flow and the classical master-slave architectures are two ways of achieving remote kinesthesia, many others are possible. For example, an interesting property of kinesthetic remote manipulation systems is that they are bilateral - the kinesthetic correspondence applies if the slave robot is used as a master. Thus, the "forward effort" architecture is also valid and has been used.[12]

Rather than review applications by industry, we will instead illustrate the diversity of telemanipulation applications through the ranges of two key parameters in teleoperation system design: the position scale factor λ_p and the force scale factor λ_f. In the forward flow architecture, position (or velocity) commands sent from the master to the slave are multiplied by λ_p, and force information from the slave is multiplied by λ_f before being applied to the operator. In other architectures, λ_p and λ_f may not be explicit parameters in the control system, but they can be derived as described below.

Up until now, telemanipulation systems have been designed to overcome barriers of **distance** between the operator and the manipulated object. Recent teleoperation developments are aimed at overcoming the barriers of **large differences of scale** between the human operator and the manipulated object.

The position scale of telemanipulation systems has today spanned an astonishing 10 orders of magnitude (Figure 1). In systems which have been implemented to date, λ_p has varied from approximately 10 in the case of the Space Shuttle Remote Manipulation System (RMS)*, to about 10^{-9} in the case of recent work teleoperating the scanning, tunneling microscope (STM) and atomic force microscope (AFM).[13,14]

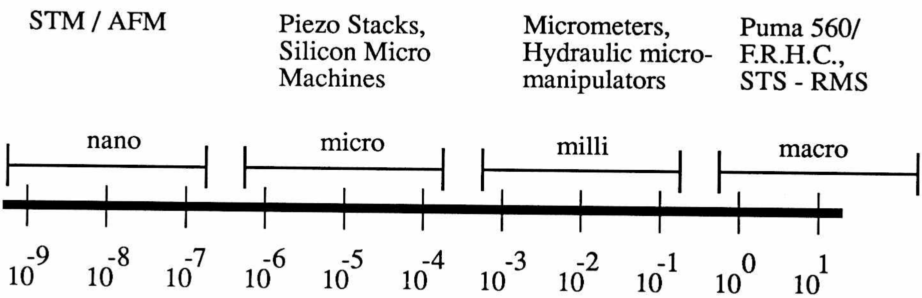

Figure 1.
Telemanipulation systems have been developed which scale the operators position commands over a wide range.

*Only resolved rate control has been used to control the RMS to date. The λ_p estimate is based on the approximate ratio of the size of the RMS to the size of the human arm.

To define some terms, ranges can be designated on the λ_p scale defining "macro-telemanipulation," $10^0 \leq \lambda_p < 10^3$; "milli-telemanipulation," $10^{-3} \leq \lambda_p < 10^0$; "micro-telemanipulation," $10^{-6} \leq \lambda_p < 10^{-3}$; and "nano-telemanipulation," $10^{-9} \leq \lambda_p < 10^{-6}$. Although these definitions haven't yet been standardized, they are beginning to achieve common usage, especially in Japan. While the specific scales associated with each range are open to debate, clearly the four terms should be separated by a factor of 10^3 and each span a range of 10^3. One difficulty with consistent terminology is that a typical robot manipulator has two relevant scales usually separated by a factor of about 1000. For example, an industrial robot may have a work volume radius of about 1 meter, and a position resolution at the end effector of about 1 mm. The terminology in this chapter is based on the position scale λ_p and thus avoids this ambiguity.

Nano-telemanipulation has leapt to attention with the STM and AFM applications in which a human controls a probe tip with atomic scale resolution. Hunter[15] has developed a six degree of freedom nano-manipulator to kinesthetically manipulate individual muscle fibers (carefully cultured together with the apparatus) during muscle physiology experiments. His system has focused primarily on delivering controlled position increments to muscle fiber preparations for nano-biomechanical tissue characterization.

Micro-telemanipulation is an area of opportunity raised by the recent development of small mechanical systems fabricated on silicon by microscopic photo-lithography and processes from the VLSI industry, but this author has not yet seem kinesthetic teleoperation implemented at this scale.

Milli-telemanipulation is widely expected to have significant impact in the field of micro-surgery,[16] micro-neurography, and electrophysiology. Additional applications under exploration at the "milli" scale include: injection of genetic material into cells, embryological research, in-vitro fertilization, and electronic assembly. Today, all of these applications are performed either with micrometer drive or hydraulic reduction drive equipment or manually.

By virtue of their huge mechanical reduction of the operator's motion through high-pitch lead screws, micrometer drives are completely rigid with respect to the delicate tissues they are manipulating. Direct human manipulation at these scales while remarkably capable, (in retinal surgery, human surgeons can "routinely" make repeatable controlled incisions as small as 200 microns[17]), is limited to a few individuals and like the micrometer drive is insensitive to the small forces generated by the tissues.

The other crucial design or operating parameter is λ_f, the force scale factor. Nominally, λ_f is the inverse of λ_p. However, the two can be varied independently to effectively adjust the impedances of the operator and task. If λ_f is plotted against λ_p, we can visualize a space in which different kinesthetic feedback applications reside (Figure 2).

The mechanical impedance felt by the operator of such a device can be derived in terms of the environment impedance Z_e. To a first approximation, it can be shown (section II-3) that the felt impedance is

$$Z_f = \lambda_p \lambda_f Z_e \qquad (1)$$

where Z_e is the mechanical impedance of the environment.

The line

$$\lambda_p = \frac{1}{\lambda_f} \qquad (2)$$

defines the locus of scale factors for which the operator's perception of the environment mechanical impedance is unscaled. Operation above the line, i.e.

$$\lambda_p > \frac{1}{\lambda_f} \qquad (3)$$

increases the perceived impedance relative to the actual load and operation below the line reduces the perceived mechanical impedance.

Similarly, power gain across the teleoperator is (section II-4)

$$\frac{P_{load}}{P_{operator}} = \frac{\lambda_p}{\lambda_f} \qquad (4)$$

Thus, the line

$$\lambda_f = \lambda_p \qquad (5)$$

defines the locus of unity power gain (passivity). Operation above the line, i.e.

$$\lambda_f > \lambda_p \qquad (6)$$

attenuates power from the operator and operation below the line amplifies