

Preface

When writing a book that is concerned with the robot's physical contact and interaction with an environment, first and foremost we ought to consider the following contradictory situation. During the last two decades, the control of robot *contact motion* (also referred to as *compliant motion*) has emerged as one of the most attractive and fruitful research areas in robotics. The initial investigations in the field were motivated by the practical needs for automating complex tasks mainly performed by humans, such as assembly, deburring, etc. The control of physical robot interaction is still a challenging research issue, recently addressing the emerging fields of human-robot interaction systems, human augmentations and enhancements, haptic rendering, rehabilitation robotics, etc. However, in spite of considerable research efforts and results achieved, the applications of compliance control in the industry and service fields are still insignificant in comparison with widespread free-space robot applications, such as pick-and-place or seam-tracking tasks. The majority of industrial robot assembly applications utilize passive compliance devices (Remote Center of Compliance - RCC) compensating for misalignments of parts with specific geometry. Other applications employ additional passive or active axes with simple compliance control algorithms. More sophisticated robotic systems that would involve the programming and control of the interaction with a complex, dynamic and variable environment are still missing in practice.

There are many different reasons for such a situation. Based on almost twenty years of research and experience with implementing the compliant-motion control algorithms in industrial and other robotic systems we would try to identify the most critical causes which in our opinion mainly inhibited a more widespread application of interactive robotic systems. First, the development of a controller for contact tasks has proven to be quite difficult, largely due to the stability problems that arise in the dynamic interaction during robot's physical contact with an environment. The interaction control problems are still insufficiently specified, and their structural relationships to classical servo control design problems and methodologies are not completely clear. One

further limitation is the absence of a widely accepted framework for the synthesis of the interaction control parameters that would ensure the stability of both the contact transition and interaction processes, and guarantee the desired contact performance. The existing design procedures based on robot passivity appear to be exceedingly conservative in the applications in which the interaction between an industrial robot and a stiff environment should be controlled. The established interaction control algorithms are mostly concerned with particular problems, usually at the lowest servo-control layer, and their integration into a complete control system, which appears to be a very tedious task, is still missing.

Further, many of the proposed control algorithms are based on the computed-torque method and are closely related to direct-drive robotic systems. The direct-drive technology is, however, still seldom used in robotic practice, due to several serious problems related to the large mass, overheating, and high costs of direct-drive actuators. On the other hand, direct-drive robots appear to be quite suitable for advanced experimental investigations of robot control in research laboratories. The popular computed-torque control technique requires real-time computation of complete dynamic models of the robot and environment, which makes its realization rather complex. This approach works reasonably well in direct-drive robots when their dynamic parameters have been correctly identified. In industrial robots, however, the performance improvements which can be achieved with these algorithms are not in proportion with the implementation efforts. Due to quite different performance, the results obtained for direct-drive robots, although experimentally verified, cannot be applied onto industrial robots. The investigations of compliant motion control are usually concerned with the nonlinear effects in robot and environment dynamics, rather than with the problems encountered in conventional robotic systems, such as Coulomb friction, control time delay, practical limitations of computer and sensory systems, etc.

Still, there is another problem concerning the knowledge of the environment model. The majority of proposed algorithms exhibit good performance only under the assumption that an accurate model of the environment and its parameters (e.g. contact location, stiffness) are available. In real stiff environments, however, this condition is quite restrictive and non-realistic, since it is difficult to identify the parameters using available sensory and computer control systems.

All these problems make the existing results of compliant motion control difficult to implement from a practical point of view. This requires further

investigation efforts on reliable and simple, but nevertheless robust, control solutions. Despite the progress that has been made during the last decade, there are still research issues insufficiently investigated, such as:

- the stability of contact transition is not clearly addressed in the literature. The reliable necessary and sufficient conditions that would ensure the maintenance of a stable contact during transition are still missing.
- the problem of handling an inadvertent loss of contact has not been solved yet.

Furthermore, of special practical importance are the following topics, deserving further computational/experimental study:

Design of robust compliance motion control to improve disturbance rejection capabilities;

- Definition of measures and criteria to evaluate the compliant motion capabilities of industrial robots in relation to performing a task, taking into account the distortion of friction and other similar disturbances in the arm;
- Comparison of the available algorithms and definition of benchmark tests;
- Development of reliable control schemes based on a unified approach to force, position and impedance control, which can be applied in conventional industrial robotic systems.

Therefore, this book is aimed at considering the interaction control problems from a broad and comprehensive point of view. The problem of robot-environment interaction control is tackled taking into account different issues, such as: mathematical modeling of contact and interaction kinematics and dynamics, stability of coupled systems and contact transition process, various interaction control algorithms and techniques, robustness against disturbances and model uncertainties, programming and planning of simple contact tasks, sampled systems control effects, as well as practical control synthesis and design for industrial implementations. Last but not least, practical knowledge and experience gained in the developing and implementing various interactive robotic systems is reflected in this book.

The contents of the book are organized as follows.

Chapter 1 provides a comprehensive review of various compliant motion control methods proposed in the literature. It covers some early ideas and their later improvements, as well as new control concepts and recent trends in this field. Before reviewing many of the results, a categorization of compliant motion tasks and proposed control concepts is established based on various

classifying criteria. In this survey, particular attention is paid not only to traditional indices of control performance, but also to the reliability and applicability of algorithms and control schemes in industrial robotic systems. These systems are widely employed in practice, providing a reasonable background for compliance motion control implementation. However, compliance control is a very attractive control approach in the new emerging technologies, such as service robotics (e.g. surgical and rehabilitation robots), virtual reality and haptics, telemanipulation, human augmentation and assistance. These fields apply new and quite different robotic structures in comparison to conventional industrial robotic systems (e.g. direct-drive robots, parallel and wire manipulators, etc.). This chapter provides a historical perspective, summarizes contributions of the most relevant or representative investigations and methods, and identifies the interaction control problems that are still open, requiring additional research efforts. It provides useful information, especially for younger roboticists having no previous work experience.

Chapter 2 is devoted to the unified approach to dynamic control of the robot interacting with a dynamic environment. The unified position-force control differs essentially from the conventional hybrid position/force control schemes. A dynamic approach to controlling simultaneously both the position and force in an environment with completely dynamic reactions has been established. The approach of dynamic interaction control defines two control subtasks responsible for the stabilization of robot position and interaction force. The both control subtasks utilize dynamic models of the robot and environment in order to ensure tracking of both the nominal motion and force. Special attention is given not only to the synthesis of control laws ensuring stability of robot's desired motions and desired interaction forces of the robot and environment, but also to the definition of possible motions of the robot and its possible interaction forces in contact tasks. The concept of the family of transient responses with respect to the robot's motion and its force of interaction with environment is formulated. It allows one to set and then solve the problem of the synthesis of control laws that not simply stabilize the motion and force of interaction of the robot with its environment, but also solves the problem of stabilization with the preset quality of transient processes. Significant attention is given to the analysis of the influence of the constraints imposed on the state, control, and interaction force on transient responses, taking into account the inadequacy of dynamics models of the robot and environment and/or external perturbations. The adaptive control scheme proposed in this chapter enables one to solve contact tasks for robots with both stationary and nonstationary dynamics. The elaborated stability test

may be used either to check the stability of the specified control laws, or to establish procedures for the synthesis of parameters of different control laws. Hence, the control synthesis becomes much more accurate and effective, i.e. higher robustness of the control to the uncertainties in the robot and environment models can be ensured, which is one of the most relevant aspects in the potential industrial applications of robots in numerous technological tasks where the robot is interacting with the environment (e.g. in cutting, deburring, etc.). The developed control algorithms also appear very promising for interaction with a virtual environment in high dynamic haptic systems, as well as for controlling novel dual-arm robots and bimanual contact tasks.

Chapter 3 is concerned with the design of compliance control algorithms that are reliable and robust for implementing in industrial robots and advanced interaction systems (e.g. haptic interfaces, surgical and rehabilitation robots, human enhancers, collaborative robots, etc.). The problems and research issues that are associated with the design of robust impedance control algorithms for stable interaction with a passive environment are in the main focus of this chapter. The basic control development problems, such as stability, performance and robustness of impedance control algorithms are addressed. These problems are considered at the lowest servo control layer. For the sake of simplicity, the impedance control design problem is split into two subproblems concerning the realization of the target impedance and selection of target impedance parameters which ensure specific desired task performance, as well as common control design requirements, such as stability, fast reaction and robustness. The stability of the interaction between the robot and environment in contact, which is essential for the impedance control synthesis, is defined by means of the *coupled stability*. For the examination of stability we have applied a common approach utilizing the properties of the system at equilibrium, and various modern control techniques (e.g. *positivity* and H_∞ control concepts, etc.). We have further considered the stability of the contact transition process. Although recognized to be most fundamental in contact tasks control synthesis, this problem has not been addressed appropriately until now. Especially, the contact stability in industrial robotic systems has not been explored adequately. Several practical contact stability definitions are proposed in order to clearly make distinction between the contact stability and coupled stability, often mistaken in the literature. Based on these definitions, new stability conditions are proposed. The concept of dynamic systems passivity and robust stability analysis are applied to obtain the reliable conditions for ensuring contact stability. The established stability criteria provide the basis for examining the effects of impedance control

parameters on the transition process stability. The analysis/synthesis oriented stability examinations allow the tuning of target impedance parameters in order to meet both interaction performance and stability. Within the robust stability analysis framework, the generalized contact stability condition is also derived, ensuring both contact and coupled system stability. The stability analysis is pursued in discrete-time and sampled-data interaction systems. In order to evaluate the derived contact stability criteria a set of several hundred contact transition experiments was designed and realized using an industrial robot. The aim was to capture a practical parametric contact stability limit in a typical real robot-environment interaction system. On the basis of tests performed it is demonstrated that the most accurate contact stability results (the parametric limits closest to the experimental bounds) provides the passivity-based criterion for the sampled-data system. Robust contact stability always ensures a safe transition and appears to be very practical for the control synthesis in an uncertain robot-environment interaction system.

Chapter 4 addresses the synthesis of the adopted second-order target impedance model for a generic contact task. The contact task consists of the realization and maintenance of a stable contact with the environment. The interaction force should be kept within the prescribed limits, dependent on the position tolerances and environmental stiffness. This assignment is intrinsically involved in almost all robot interaction tasks. The chapter considers the algorithms for the practical impedance control design in industrial robotic systems. The developed algorithms integrate the theoretical and practical stability results dealt with in the previous chapter. The considered impedance control synthesis addresses basic control design problems at the servo-control layer. The impedance control design has been established for a reliable decoupled compliance geometric model that allows a relatively simple parameterization of the target impedance behavior. For the fundamental and common interaction tasks, the compliance parameters can be chosen independently of the interaction system configuration. More complex robot-environment interactions were also considered based on the spatial compliance model. The control synthesis consists of the straightforward steps of computing the target impedance parameters and impedance compensator gains. All input parameters to the design algorithm have been explicitly specified. The feasibility of the developed algorithms was demonstrated using experiments with two industrial robot systems. Finally, a reliable geometric and control framework for the implementation of compliance control in industrial and other advanced robotic systems has been developed and presented. Several practical and robust

control algorithms at higher planning and programming control layers were designed and tested. The essential algorithms support setting of the compliance parameters, such as the C-frame location and impedance gains, as well as continuous switching of compliance control and variation of parameters. These features are proven to be essential for a stable and robust execution of the compliance control tasks. Powerful sets of control functions, also presented in this chapter, integrate the basic compliance control algorithms in the forward robot control. These functions perform all of the computations and management of the parameters between the convenient robot position control system and impedance control kernel. Finally, some new commands, providing a flexible user-interface, are designed and implemented in a high-level robot programming environment. The new programming language commands are illustrated by means of several examples. An essential design requirement was to combine the user's experience with robot motion programming and simple understandable physical behavior of the impedance control which mimics a variable spatial mass-damper-spring system. The experimental testing within the space control system SPARCO has clearly proven the reliability and robustness of the presented high-level compliance control algorithms. Certainly, a basic precondition for the implementation of compliant motion control is the design of a robust servo impedance controller, which ensures stable transition and coupling with the environment. However, the control integration and programming issues, which are often underestimated in the literature, are essential for a customary and efficient application of impedance control in practical contact tasks. A proper selection of the C-frame location and target impedance gains is crucial for a successful execution of the impedance control tasks. This selection should be compatible with the very nature of the motion constraints, i.e. contact task geometry and physical task characteristics (e.g. force-motion relationships). The experience gained in performing the compliance tasks presented here is essential for compliance control design and implementation in a wide range of tasks in industrial and service robotics.

The robust control framework and the new contact stability theory established for the control synthesis of the interaction between an impedance-controlled robot and a passive environment are expanded in *Chapter 5* to the control and synthesis of haptic interfaces interacting with a virtual environment. This rapidly emerging technology imposes high requirements on the interaction stability and robustness of the control system in spite of considerable control computation efforts and time lags. Recently, the new interactive systems concerning the interaction between a human and a robotic device, as well as with robot's physical or virtual dynamic environments, have aroused a strong research

interest. To the novel interactive systems belong kinesthetic displays and haptic interfaces, teleoperation systems, human enhancers and augmentation devices, rehabilitation robots, robot assistants and collaborative robots, etc. These systems are designed to produce/receive kinesthetic stimuli for/from human movements, as well as to provide the user with a realistic feeling of the contact and dynamic interaction with the close, remote or virtual environments. The advanced interaction systems have recently found very attractive applications in surgical and rehabilitation robotics, power assist-devices, training simulation systems, etc. The most critical issue in these systems is how to ensure stable and safe interaction with a high fidelity of reproduction of a virtual environment. This is a challenging task when taking into account serious problems such as unknown and variable human dynamics, commonly non-linear environmental characteristics, as well as various disturbances in computer-controlled systems. This chapter considers the stability of the interaction of a human-robot-environment (real or virtual) system based on the robust control design approach. The proposed new interaction stability paradigm ensures contact stability during all phases of the interaction. Moreover, the new design framework realizes low-impedance performance allowing considerable reduction of high apparent industrial robot inertia and stiffness. The defined stability indices take into account the relevant effects in the robot control systems, such as time lags and sampling data effects, as well as the uncertainties in the environment and realized target admittance models. The synthesis of robust control laws is confirmed to be very efficient for the stabilization of the interaction between a robot and a stiff and force-delayed environment taking into account the desired interaction performance. The testing of this approach in various robotic systems demonstrates the feasibility and reliability of the interaction control approach even for relatively high control rates and lags. The advantage of robust stability is particularly demonstrated in the interaction control of novel intelligent power-assist handling systems with significant perturbations in the force and position measurements. This shows the practical applicability of the novel stability criteria for haptic systems.

Chapter 6 covers some advanced control techniques. As robotic systems make their way into standard practice, they have opened the door to a wide spectrum of complex applications. Such applications usually demand highly intelligent robots. Future robots are likely to have greater sensory capabilities, more intelligence, higher levels of manual dexterity, and the mobility, compared to humans. In order to ensure high-quality control and performance in robotics, new intelligent control techniques must be developed that will be capable of

coping with task complexity, multi-objective decision making, large volumes of perception data and substantial amounts of heuristic information. Soft Computing paradigms consisting of complementary elements of Fuzzy Logic, Neural Computing and Evolutionary Computation are viewed as the most promising methods towards intelligent robotic systems. The specific emphasis in research is given on the development of efficient learning rules for robotic connectionist training and synthesis of neural learning algorithms for low-level control in the domain of robotic compliance tasks. The synthesis of new advanced learning algorithms for robotic contact tasks by nonrecurrent and recurrent connectionist structures is presented in this chapter as the main research contribution. The main concern of this chapter, which provides a survey of connectionist algorithms for robotic contact tasks, is the development of learning control algorithms as an upgrade of conventional non-learning control laws for robotic compliance tasks (algorithms for stabilization of robot motion, stabilization of robot interaction force and impedance algorithms). In view of the important influence of the robot environment, a new comprehensive learning approach, based on simultaneous classification of robot environment and learning of robot uncertainties, is also presented.

The book is addressed to a wide audience of scientists, practitioners and scholars dealing with interactive robotic systems. It is our hope that the material presented in this book will be useful to a wide range of readers, ranging from undergraduate and graduate students, new and advanced academic researchers, to the technical specialists (mechanical, electrical, computer or systems engineers). It can also be adopted as a textbook for a graduate course on advanced robotic systems.

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