Multimedia Contents

Part A Robotics Foundations

Ed. by David E. Orin

The chapters contained in Part A, Robotics Foundations, present the fundamental principles and methods that are used to develop a robotic system. In order to perform the tasks that are envisioned for robots, many challenging problems have been uncovered in kinematics, dynamics, design, actuation, sensing, modeling, motion planning, control, programming, decision-making, task planning, and learning. Robots with redundant kinematic degrees of freedom or with flexible elements add to the complexity of these systems. The chapters in this part address the basic issues in each of these areas.

Some of the basic problems in robotics are outlined as follows. Robots often consist of a large number of degrees of freedom so that they can provide the rich set of three-dimensional (3-D) motions that may be required for a range of tasks. The kinematic and dynamic relationships between the joint actuators' motion and torques, and the desired motion and force for a task can be very complex. The design of the link and joint structures, as well as the actuation, to achieve the desired performance is also challenging.

The robot is a nonlinear, coupled system which is difficult to model and control because of its complex dynamics. Kinematic redundancy and flexible elements in the robots increase this complexity. The problem is exacerbated when the environment is unstructured, and often sophisticated sensing and estimation techniques are required.

In addition to control of the motion, control of the interaction forces between the robot and environment is needed when manipulating objects or interacting with humans. A fundamental robotics task is to plan collision-free motion for complex bodies from a start to a goal position among a collection of obstacles, and this can become an intractable computational problem.

In order to achieve some of the intelligence ascribed to humans, robots will need to be equipped with sophisticated action planners that employ symbolic reasoning to move in dynamic, partially known environments. In other scenarios, robots need to execute behaviors that take advantage of dynamic interactions with the environment rather than rely solely on explicit reasoning and planning. Robot software architectures also have special needs because of all of these requirements. Robot learning will be necessary to generate actions and control for ever-changing task requirements and environments, in order to achieve the level of autonomy envisioned.

While the basic issues outlined in the previous paragraphs are addressed in this part, more depth can be found in other parts of the handbook. The kinematics, dynamics, mechanical design, and control principles and methods introduced in this part can be applied to robotic structures made up of arms, hands, and legs (Part B) as well as manipulators (Part D), wheeled and other mobile robots (Part E), and field and service robots (Part F). Force control is especially important for manipulators and their interfaces (Part D). The basic sensing and estimation techniques presented here are expanded and applied to specific sensing modalities in Part C. Motion planning is an important aspect of manipulation (Part D) and mobile robots moving in the environment (Part E). Robotic systems architectures, behavior-based systems, artificial intelligence (AI) reasoning methods, and robot learning are particularly important in mobile robots moving in the environment (Part E) and robots interacting with humans (Part G).

With this overview of Part A, we now provide a brief synopsis of each chapter:

Chapter 2, Kinematics, provides a number of representations and conventions to describe the motion of the bodies in a robotic mechanism. These include rotation matrices, Euler angles, quaternions, homogeneous transformations, screw transformations, matrix exponential parameterization, and Plücker coordinates. Representations of the kinematics of all common joint types are provided, along with a modified form of the Denavit–Hartenberg convention. These representational tools are applied to compute the workspace, the forward and inverse kinematics, the forward and inverse instantaneous kinematics, Jacobian, and the static wrench transmission.

Chapter 3, Dynamics, presents the dynamic equations of motion which provide the relationships between actuation and contact forces acting on robot mechanisms, and the acceleration and motion trajectories that result. Efficient algorithms are provided for important dynamics computations which include inverse dynamics, forward dynamics, the joint-space inertia matrix, and the operational-space inertia matrix. The algorithms may be applied to fixed-base robots, mobile robots, and parallel robot mechanisms. Compact formulation of the algorithms results from using six-dimensional (6-D) spatial notation to describe rigid-body velocity, acceleration, inertia, etc.

Chapter 4, Mechanisms and Actuation, focuses on the principles that guide the design and construction of robotic systems. The kinematic equations and Jacobian are used to characterize the work envelope and mechanical advantage, and guide the selection of the robot's size and joint arrangement. The design of both serial and parallel robots is addressed. Practical consideration is given to the design of the link and joint structures along with selection of the actuators and transmission drives to power the movement. Robot performance in terms of speed, acceleration, repeatability, and other measures is also addressed.

Chapter 5, Sensing and Estimation, provides a brief overview of common sensing methods and estimation techniques that have found broad applicability in robotics. These provide information about the state of the environment and robot system. The presentation is structured according to a perception process model that includes sensing, feature extraction, data association, parameter estimation and model integration. Several common sensing modalities are introduced and characterized. Methods for estimation in linear and nonlinear systems are discussed, including statistical estimation, the Kalman filter, and sample-based methods. The several common representations for estimation are also introduced.

Chapter 6, Model Identification, discusses methods for determining the kinematic and inertial parameters of robot manipulators. For kinematic calibration, the primary aim is to identify the geometric Denavit–Hartenberg parameters or equivalent, typically by sensing a combination of joint and endpoint positions. Inertial parameters in turn are estimated through the execution of a trajectory while additionally sensing one or more components of joint forces or torques. The chapter is organized such that both kinematic and inertial parameter identification are cast into a common framework of least-squares parameter estimation: common features relating to the identifiability of the parameters, adequacy of the measurement sets, and numerical robustness are identified and emphasized for both the kinematic and inertial parameters.

Chapter 7, Motion Planning, addresses the fundamental robotics task to plan collision-free motion for complex bodies from a start to a goal position among a collection of obstacles. The basic geometric path planning problem (Piano Mover's problem) is introduced, but the focus of the chapter is on sampling-based planning methods because of their generally wider applicability. Planning with differential constraints is considered and is important for wheeled mobile robots. Extensions and variations to the basic motion planning problem, as well as advanced issues, are discussed at the end of the chapter.

Chapter 8, Motion Control, focuses on the control of the motion of a rigid manipulator. The main challenges addressed are the complexity of the nonlinear, coupled dynamics and the model structural uncertainties. The chapter discusses topics ranging from independent-joint control and PID (proportional–integral–derivative) control to computed-torque control to manage the complex dynamics. Operational space (or task space) control is presented, and this is needed for control of tasks such as those associated with the end-effector. Adaptive and robust control are discussed to address the problems related to the uncertainties in the system. Other topics presented include trajectory generation, digital implementation, and learning control.

Chapter 9, Force Control, focuses on the control of the interaction forces between a robotic system and its environment. The chapter groups interaction control in two categories: indirect and direct force control, which achieve the control without (indirect) or with (direct) explicit closure of a force feedback loop. Impedance control and hybrid force/motion control are examples of each, respectively. The fundamental problem of interaction tasks modeling is presented to provide the basis for the force control schemes.

Chapter 10, Redundant Robots, addresses the motion generation and control of manipulators with redundant kinematic degrees of freedom. Kinematic redundancy affords a robot with an increased level of dexterity that may be used to, e.g., avoid singularities, joint limits and workspace obstacles, and also to minimize joint torques, energy, or other suitable performance criteria. The chapter discusses inverse kinematic redundancy resolution schemes which are arranged in two main categories, namely those based on the optimization of suitable performance criteria and those relying on the augmentation of the task space. The use of kinematic redundancy for fault tolerance is also analyzed.

Chapter 11, Robots with Flexible Elements, addresses the dynamic modeling and control of robots with flexibility in the joints and links. Because the control methods developed to compensate for joint versus link flexibility are structurally different, the chapter is organized such that these two types of flexibility are examined independently. The methods, however, can be extended to the case when both joint and link flexibilities are present, possibly even dynamically interacting at the same time. The chapter also examines the typical sources of flexibility in industrial robots.

Chapter 12, Robotic Systems Architectures and Programming, presents the software architectures and supporting programming tools and environments that have been developed for robotic systems. Robot architectures have special needs because of the requirements of the robot to interact asynchronously, in real time, with an uncertain, often dynamic, environment. The chapter discusses the major types of architectural components for a layered robot control architecture – behavioral control, executives, and task planners – along with the commonly used techniques for interconnecting these components.

Chapter 13, Behavior-Based Systems, describes a control methodology aimed at situated robots operating in unconstrained, challenging, and dynamic conditions in the real world. Distributed behaviors are used as the underlying building blocks, allowing behavior-based systems to take advantage of dynamic interactions with the environment rather than rely solely on explicit reasoning and planning. The focus of the chapter is to provide the basic principles of behavior-based systems and their use in autonomous control problems and applications. The chapter presents several different classes of learning methods, but in all cases behaviors are used as the underlying building blocks for the learning process.

Chapter 14, AI Reasoning Methods for Robotics, sketches the main robotics-relevant topics of symbol-based AI reasoning. Reasoning on a mobile robot is especially challenging because of its dynamic, partially known environment. This chapter describes basic methods of knowledge representation and inference, covering both logic- and probability-based approaches. Results for several types of practical, robotics-related reasoning tasks are given, with an emphasis on temporal and spatial reasoning. Plan-based robot control is described in some detail, as it is a particularly obvious form of employing reasoning to the end of improving robot action.

Chapter 15, Robot Learning, surveys work in machine learning for techniques that are used for learning control and behavior generation in robots. In the future, robots will no longer be used to only execute the same task thousands of times, but rather they will be faced with thousands of different tasks that rarely repeat in an ever-changing environment. Robot learning will be necessary to achieve the high degree of autonomy envisioned. This chapter focuses on the core robot learning approaches capable of learning action generation and control, and in particular, techniques for model learning and reinforcement learning.

Part A presents the fundamental principles and methods that are used to model, design, and control a robotic system. All of the foundational topics are included in this part: kinematics, dynamics, mechanisms and actuation, sensing and estimation, model identification, motion planning, motion control, force control, redundant robots, robots with flexible elements, robotic systems architectures and programming, behavior-based systems, AI reasoning methods for robotics, and robot learning. A chapter is devoted to each of these topics. The topics are expanded and applied to specific robotic structures and systems in subsequent parts.