Robotics Part A

Part A Robotics Foundations

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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, motion planning, control, programming, and task planning. 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 control because of its complex dynamics. This 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 need to be equipped with sophisticated task planners that employ symbolic reasoning to move in dynamic, partially known environments. Robot software architectures also have special needs because of these requirements.

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 to manipulators (Part D), wheeled 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 and distributed robotic systems (Part E). Robotic systems architectures and AI reasoning methods are particularly important in mobile and distributed robotics (Part E) and human-centered and lifelike robotics (Part G).

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

`Chapter 1`, 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, the Jacobian, and the static wrench transmission.

`Chapter 2`, 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 3`, 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 4`, 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 charac-

terized. 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 5, 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 (the 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 6, Motion Control, focuses on the motion control of a rigid manipulator. The main challenges addressed are the complexity of the nonlinear, coupled dynamics and the structured and unstructured uncertainties. The chapter discusses topics ranging from independent-joint control and PID control to computed-torque control to manage the complex dynamics. Adaptive and robust control are presented to address the problems related to the uncertainties in the system. The chapter concludes with some practical considerations of digital implementation and learning control for repetitive motions.

Chapter 7, Force Control, focuses on the control of the interaction forces between a robotic system and its environment. The chapter groups interaction control into 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 8, 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 9, AI Reasoning Methods for Robotics, sketches the state of the art in artificial intelligence for the symbol-based reasoning methods and applications considered most relevant for robotics. Reasoning on a mobile robot is especially challenging because of its dynamic, partially known environment. The chapter describes knowledge representation and inference, covering both logics- and probability-based approaches. Besides reasoning methods, the chapter considers generic reasoning applications, namely, action planning and robot learning.