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# Home reading. Robot Modeling and Control by Mark W. Spong, Seth Hutchinson, and M. Vidyasagar

## Оглавление



## Текст для письменного перевода (20 000 знаков)

*Robotics is a relatively young field of modern technology that crosses tra- ditional engineering boundaries. Understanding the complexity of robots and their applications requires knowledge of electrical engineering, mechanical engi- neering, systems and industrial engineering, computer science, economics, and mathematics. New disciplines of engineering, such as manufacturing engineer- ing, applications engineering, and knowledge engineering have emerged to deal with the complexity of the field of robotics and factory automation.*

*This book is concerned with fundamentals of robotics, including kinematics, dynamics, motion planning, computer vision, and control. Our goal is to provide a complete introduction to the most important concepts in these subjects as applied to industrial robot manipulators, mobile robots, and other mechanical systems. A complete treatment of the discipline of robotics would require several volumes. Nevertheless, at the present time, the majority of robot applications deal with industrial robot arms operating in structured factory environments so that a first introduction to the subject of robotics must include a rigorous treatment of the topics in this text.*

*The term robot was first introduced into our vocabulary by the Czech play- wright Karel Capek in his 1920 play Rossum's Universal Robots, the word robota being the Czech word for work. Since then the term has been applied to a great variety of mechanical devices, such as teleoperators, underwater vehi- cles, autonomous land rovers, etc. Virtually anything that operates with some degree of autonomy, usually under computer control, has at some point been called a robot. In this text the term robot will mean a computer controlled industrial manipulator of the type shown in Figure 1.1. This type of robot is essentially a mechanical arm operating under computer control. Such devices, though far from the robots of science fiction, are nevertheless extremely com- plex electro-mechanical systems whose analytical description requires advanced methods, presenting many challenging and interesting research problems.*

*An official definition of such a robot comes from the Robot Institute of America (RIA): A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.*

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*The key element in the above definition is the reprogrammability of robots.*

*It is the computer brain that gives the robot its utility and adaptability. The so-called robotics revolution is, in fact, part of the larger computer revolution.*

*Even this restricted version of a robot has several features that make it at- tractive in an industrial environment. Among the advantages often cited in favor of the introduction of robots are decreased labor costs, increased preci- sion and productivity, increased flexibility compared with specialized machines, and more humane working conditions as dull, repetitive, or hazardous jobs are performed by robots.*

*The robot, as we have defined it, was born out of the marriage of two ear- lier technologies: teleoperators and numerically controlled milling ma- chines. Teleoperators, or master-slave devices, were developed during the sec- ond world war to handle radioactive materials. Computer numerical control (CNC) was developed because of the high precision required in the machining of certain items, such as components of high performance aircraft. The first robots essentially combined the mechanical linkages of the teleoperator with the autonomy and programmability of CNC machines.*

*The first successful applications of robot manipulators generally involved some sort of material transfer, such as injection molding or stamping, where the robot merely attends a press to unload and either transfer or stack the finished parts. These first robots could be programmed to execute a sequence of movements, such as moving to a location A, closing a gripper, moving to a location B, etc., but had no external sensor capability. More complex appli- cations, such as welding, grinding, deburring, and assembly require not only more complex motion but also some form of external sensing such as vision, tactile, or force-sensing, due to the increased interaction of the robot with its environment.*

*It should be pointed out that the important applications of robots are by no means limited to those industrial jobs where the robot is directly replacing a human worker. There are many other applications of robotics in areas where the use of humans is impractical or undesirable. Among these are undersea and planetary exploration, satellite retrieval and repair, the defusing of explosive devices, and work in radioactive environments. Finally, prostheses, such as artificial limbs, are themselves robotic devices requiring methods of analysis and design similar to those of industrial manipulators.*

*1.1*

*MATHEMATICAL MODELING OF ROBOTS*

*While robots are themselves mechanical systems, in this text we will be pri- marily concerned with developing and manipulating mathematical models for robots. In particular, we will develop methods to represent basic geometric as- pects of robotic manipulation, dynamic aspects of manipulation, and the various sensors available in modern robotic systems. Equipped with these mathematical models, we will be able to develop methods for planning and controlling robot*

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*motions to perform specified tasks. Here we describe some of the basic ideas that are common in developing mathematical models for robot manipulators.*

*1.1.1*

*Symbolic Representation of Robots*

*Robot Manipulators are composed of links connected by joints to form a kine- matic chain. Joints are typically rotary (revolute) or linear (prismatic). A revolute joint is like a hinge and allows relative rotation between two links. A prismatic joint allows a linear relative motion between two links. We denote revolute joints by R and prismatic joints by P, and draw them as shown in Figure 1.2. For example, a three-link arm with three revolute joints is an RRR arm.*

*Each joint represents the interconnection between two links. We denote the axis of rotation of a revolute joint, or the axis along which a prismatic joint translates by zi if the joint is the interconnection of links i and i + 1. The joint variables, denoted by θ for a revolute joint and d for the prismatic joint, represent the relative displacement between adjacent links. We will make this precise in Chapter 3.*

*1.1.2*

*The Configuration Space*

*A configuration of a manipulator is a complete specification of the location of every point on the manipulator. The set of all possible configurations is called the configuration space. In our case, if we know the values for the joint variables (i.e., the joint angle for revolute joints, or the joint offset for prismatic joints), then it is straightforward to infer the position of any point on the manipulator, since the individual links of the manipulator are assumed to be rigid, and the base of the manipulator is assumed to be fixed. Therefore, in this text, we will represent a configuration by a set of values for the joint variables. We will denote this vector of values by q, and say that the robot is in configuration q when the joint variables take on the values q1 · · · qn , with qi = θi for a revolute joint and qi = d1 for a prismatic joint.*

*An object is said to have n degrees-of-freedom (DOF) if its configuration can be minimally specified by n parameters. Thus, the number of DOF is equal to the dimension of the configuration space. For a robot manipulator, the num- ber of joints determines the number DOF. A rigid object in three-dimensional space has six DOF: three for positioning and three for orientation (e.g., roll, pitch and yaw angles). Therefore, a manipulator should typically possess at least six independent DOF. With fewer than six DOF the arm cannot reach every point in its work environment with arbitrary orientation. Certain appli- cations such as reaching around or behind obstacles may require more than six DOF. A manipulator having more than six links is referred to as a kinemat- ically redundant manipulator. The difficulty of controlling a manipulator increases rapidly with the number of links.*

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*1.1.3*

*The State Space*

*A configuration provides an instantaneous description of the geometry of a manipulator, but says nothing about its dynamic response. In contrast, the state of the manipulator is a set of variables that, together with a description of the manipulator's dynamics and input, are sufficient to determine any future state of the manipulator. The state space is the set of all possible states.*

*In the case of a manipulator arm, the dynamics are Newtonian, and can be specified by generalizing the familiar equation $F = ma$. Thus, a state of the manipulator can be specified by giving the values for the joint variables $q$ and for joint velocities $\dot{q}$ (acceleration is related to the derivative of joint velocities).*

*We typically represent the state as a vector $x = (q, \dot{q})T$ . The dimension of the state space is thus $2n$ if the system has $n$ DOF.*

*1.1.4*

*The Workspace*

*The workspace of a manipulator is the total volume swept out by the end- effector as the manipulator executes all possible motions. The workspace is constrained by the geometry of the manipulator as well as mechanical con- straints on the joints. For example, a revolute joint may be limited to less than a full 360◦ of motion. The workspace is often broken down into a reach- able workspace and a dexterous workspace. The reachable workspace is the entire set of points reachable by the manipulator, whereas the dexterous workspace consists of those points that the manipulator can reach with an ar- bitrary orientation of the end-effector. Obviously the dexterous workspace is a subset of the reachable workspace. The workspaces of several robots are shown later in this chapter.*

*1.2*

*ROBOTS AS MECHANICAL DEVICES*

*There are a number of physical aspects of robotic manipulators that we will not necessarily consider when developing our mathematical models. These include mechanical aspects (e.g., how are the joints actually implemented), accuracy and repeatability, and the tooling attached at the end effector. In this section, we briefly describe some of these.*

*1.2.1*

*Classification of Robotic Manipulators*

*Robot manipulators can be classified by several criteria, such as their power source, or way in which the joints are actuated, their geometry, or kinematic structure, their intended application area, or their method of control. Such classification is useful primarily in order to determine which robot is right for a given task. For example, a hydraulic robot would not be suitable for food* *handling or clean room applications. We explain this in more detail below. Power Source. Typically, robots are either electrically, hydraulically, or pneu- matically powered. Hydraulic actuators are unrivaled in their speed of response and torque producing capability. Therefore hydraulic robots are used primar- ily for lifting heavy loads. The drawbacks of hydraulic robots are that they tend to leak hydraulic fluid, require much more peripheral equipment (such as pumps, which require more maintenance), and they are noisy. Robots driven by DC- or AC-servo motors are increasingly popular since they are cheaper, cleaner and quieter. Pneumatic robots are inexpensive and simple but cannot be controlled precisely. As a result, pneumatic robots are limited in their range of applications and popularity.*

*Application Area. Robots are often classified by application into assembly and non-assembly robots. Assembly robots tend to be small, electrically driven and either revolute or SCARA (described below) in design. The main nonassembly application areas to date have been in welding, spray painting, material handling, and machine loading and unloading.*

*Method of Control. Robots are classified by control method into servo and non-servo robots. The earliest robots were non-servo robots. These robots are essentially open-loop devices whose movement is limited to predetermined mechanical stops, and they are useful primarily for materials transfer. In fact, according to the definition given previously, fixed stop robots hardly qualify as robots. Servo robots use closed-loop computer control to determine their motion and are thus capable of being truly multifunctional, reprogrammable devices.*

*Servo controlled robots are further classified according to the method that the controller uses to guide the end-effector. The simplest type of robot in this class is the point-to-point robot. A point-to-point robot can be taught a discrete set of points but there is no control on the path of the end-effector in between taught points. Such robots are usually taught a series of points with a teach pendant. The points are then stored and played back. Point-to-point robots are severely limited in their range of applications. In continuous path robots, on the other hand, the entire path of the end-effector can be controlled. For example, the robot end-effector can be taught to follow a straight line between two points or even to follow a contour such as a welding seam. In addition, the velocity and/or acceleration of the end-effector can often be controlled. These are the most advanced robots and require the most sophisticated computer controllers and software development.*

*Geometry. Most industrial manipulators at the present time have six or fewer degrees-of-freedom. These manipulators are usually classified kinematically on the basis of the first three joints of the arm, with the wrist being described separately. The majority of these manipulators fall into one of five geometric types: articulated (RRR), spherical (RRP), SCARA (RRP), cylindri- cal (RPP), or Cartesian (PPP). We discuss each of these below. Each of these five manipulator arms are serial link robots. A sixth distinct class of manipulators consists of the so-called parallel robot. In a parallel manipulator the links are arranged in a closed rather than open kinematic chain. Although we include a brief discussion of parallel robots in this chapter, their kinematics and dynamics are* *more difficult to derive than those of serial link robots and hence are usually treated only in more advanced texts.*

*1.2.2*

*Robotic Systems*

*A robot manipulator should be viewed as more than just a series of mechanical linkages. The mechanical arm is just one component in an overall Robotic System, illustrated in Figure 1.3, which consists of the arm, external power source, end-of-arm tooling, external and internal sensors, computer interface, and control computer. Even the programmed software should be considered as an integral part of the overall system, since the manner in which the robot is programmed and controlled can have a major impact on its performance and subsequent range of applications.*

*1.2.3*

*Accuracy and Repeatability*

*The accuracy of a manipulator is a measure of how close the manipulator can come to a given point within its workspace. Repeatability is a measure of how close a manipulator can return to a previously taught point. The primary method of sensing positioning errors in most cases is with position encoders located at the joints, either on the shaft of the motor that actuates the joint or on the joint itself. There is typically no direct measurement of the end-effector position and orientation. One must rely on the assumed geometry of the manip- ulator and its rigidity to infer (i.e., to calculate) the end-effector position from the measured joint positions. Accuracy is affected therefore by computational errors, machining accuracy in the construction of the manipulator, flexibility effects such as the bending of the links under gravitational and other loads, gear backlash, and a host of other static and dynamic effects. It is primarily for this reason that robots are designed with extremely high rigidity. Without high rigidity, accuracy can only be improved by some sort of direct sensing of the end-effector position, such as with vision.*

*Once a point is taught to the manipulator, however, say with a teach pen- dant, the above effects are taken into account and the proper encoder values necessary to return to the given point are stored by the controlling computer.*

*Repeatability therefore is affected primarily by the controller resolution. Con- troller resolution means the smallest increment of motion that the controller can sense. The resolution is computed as the total distance traveled by the tip divided by 2n , where n is the number of bits of encoder accuracy. In this context, linear axes, that is, prismatic joints, typically have higher resolution than revolute joints, since the straight line distance traversed by the tip of a linear axis between two points is less than the corresponding arc length traced by the tip of a rotational link.*

*In addition, as we will see in later chapters, rotational axes usually result in a large amount of kinematic and dynamic coupling among the links with a resultant accumulation of errors and a* *more difficult control problem. One may wonder then what the advantages of revolute joints are in manipulator design.*

*The answer lies primarily in the increased dexterity and compactness of revolute joint designs. For example, Figure 1.4 shows that for the same range of motion, a rotational link can be made much smaller than a link with linear motion. Thus manipulators made from revolute joints occupy a smaller working volume than manipulators with linear axes. This increases the ability of the manipulator to work in the same space with other robots, machines, and people. At the same time revolute joint manipulators are better able to maneuver around obstacles and have a wider range of possible applications.*

*1.2.4*

*Wrists and End-Effectors*

*The joints in the kinematic chain between the arm and end effector are referred to as the wrist. The wrist joints are nearly always all revolute. It is increasingly common to design manipulators with spherical wrists, by which we mean wrists whose three joint axes intersect at a common point. The spherical wrist is represented symbolically in Figure 1.5. The spherical wrist greatly simplifies the kinematic analysis, effectively al- lowing one to decouple the positioning and orientation of the end effector. Typ- ically therefore, the manipulator will possess three degrees-of-freedom for posi- tion, which are produced by three or more joints in the arm. The number of degrees-of-freedom for orientation will then depend on the degrees-of-freedom of the wrist. It is common to find wrists having one, two, or three degrees-of- freedom depending of the application. For example, the SCARA robot shown in Figure 1.14 has four degrees-of-freedom: three for the arm, and one for the wrist, which has only a rotation about the final z-axis.*

*It has been said that a robot is only as good as its hand or end-effector.*

*The arm and wrist assemblies of a robot are used primarily for positioning the end-effector and any tool it may carry. It is the end-effector or tool that actually performs the work. The simplest type of end-effectors are grippers, which usually are capable of only two actions, opening and closing. While this is adequate for materials transfer, some parts handling, or gripping simple tools, it is not adequate for other tasks such as welding, assembly, grinding, etc. A great deal of research is therefore devoted to the design of special pur- pose end-effectors as well as to tools that can be rapidly changed as the task dictates. There is also much research on the development of anthropomorphic hands. Such hands have been developed both for prosthetic use and for use in manufacturing. Since we are concerned with the analysis and control of the manipulator itself and not in the particular application or end-effector, we will not discuss end-effector design or the study of grasping and manipulation.*

*...*