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What Does "Control of Robots" Involve?

The present textbook focuses on the interaction between robotics and electrical engineering and more specifically, in the area of *automatic control*. From this interaction emerges what we call *robot control*.

Loosely speaking (in this textbook), robot control consists in studying how to make a robot manipulator perform a task and in materializing the results of this study in a lab prototype.

In spite of the numerous existing commercial robots, robot control design is still a field of intensive study among robot constructors and research centers. Some specialists in automatic control might argue that today's industrial robots are already able to perform a variety of complex tasks and therefore, at first sight, the research on robot control is not justified anymore. Nevertheless, not only is research on robot control an interesting topic by itself but it also offers important theoretical challenges and more significantly, its study is indispensable in specific tasks which cannot be performed by the present commercial robots.

As a general rule, control design may be divided roughly into the following steps:

- familiarization with the physical system under consideration;
- modeling;
- control specifications.

In the sequel we develop further on these stages, emphasizing specifically their application in robot control.

1.1 Familiarization with the Physical System under Consideration

On a general basis, during this stage one must determine the physical variables of the system whose behavior is desired to control. These may be temperature, pressure, displacement, velocity, *etc.* These variables are commonly referred to as the system's *outputs*. In addition to this, we must also clearly identify those variables that are available and that have an influence on the behavior of the system and more particularly, on its outputs. These variables are referred to as *inputs* and may correspond for instance, to the opening of a valve, voltage, torque, force, *etc.*

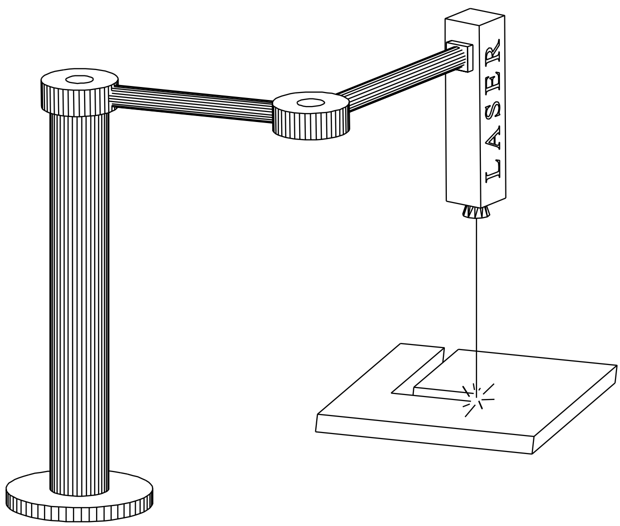

Figure 1.1. Freely moving robot

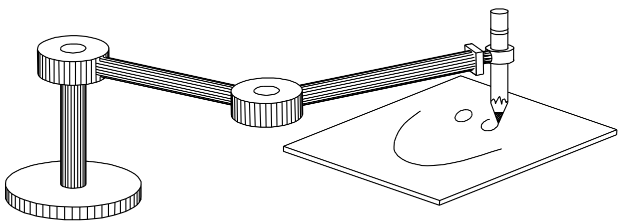

Figure 1.2. Robot interacting with its environment

In the particular case of robot manipulators, there is a wide variety of outputs – temporarily denoted by $\boldsymbol{y}$ – whose behavior one may wish to control.

For robots moving freely in their *workspace*, *i.e.* without interacting with their environment (*cf.* Figure 1.1) as for instance robots used for painting, "pick and place", laser cutting, *etc.*, the output $\boldsymbol{y}$ to be controlled, may correspond to the joint positions $\boldsymbol{q}$ and joint velocities $\dot{\boldsymbol{q}}$ or alternatively, to the position and orientation of the end-effector (also called end-tool).

For robots such as the one depicted in Figure 1.2 that have physical contact with their environment, *e.g.* to perform tasks involving polishing, deburring of materials, high quality assembling, *etc.*, the output $\boldsymbol{y}$ may include the torques and forces $\boldsymbol{f}$ exerted by the end-tool over its environment.

Figure 1.3 shows a manipulator holding a marked tray, and a camera which provides an image of the tray with marks. The output $\boldsymbol{y}$ in this system may correspond to the coordinates associated to each of the marks with reference to a screen on a monitor. Figure 1.4 depicts a manipulator whose end-effector has a camera attached to capture the scenery of its environment. In this case, the output $\boldsymbol{y}$ may correspond to the coordinates of the dots representing the marks on the screen and which represent visible objects from the environment of the robot.

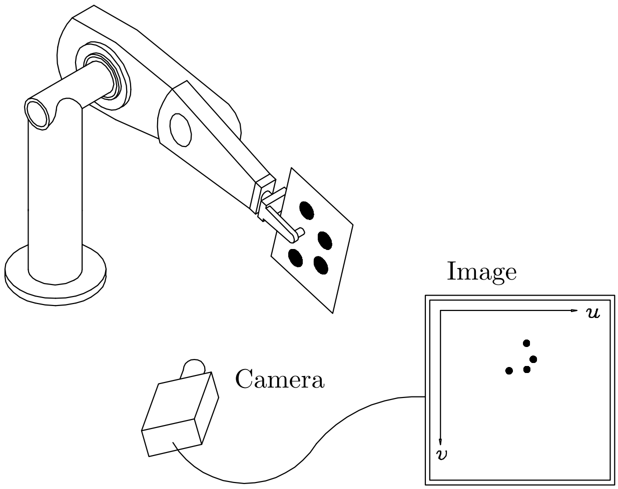

Figure 1.3. Robotic system: fixed camera

From these examples we conclude that the corresponding output $\boldsymbol{y}$ of a robot system – involved in a specific class of tasks – may in general, be of the form

$$\boldsymbol{y} = \boldsymbol{y}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{f})\,.$$

On the other hand, the input variables, that is, those that may be modified to affect the evolution of the output, are basically the torques and forces $\boldsymbol{\tau}$ applied by the actuators over the robot's joints. In Figure 1.5 we show

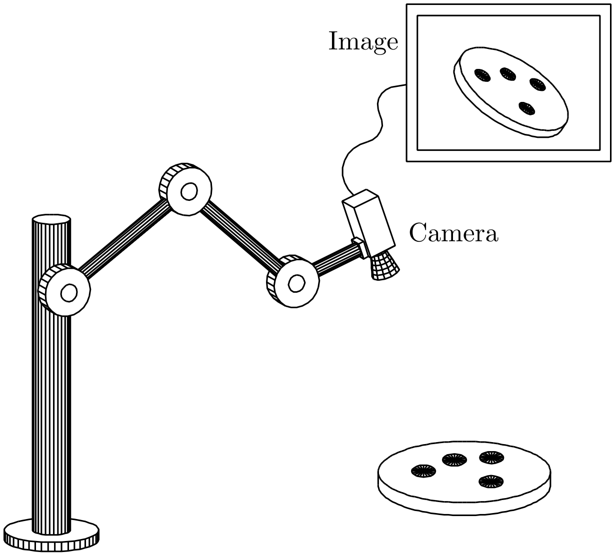

Figure 1.4. Robotic system: camera in hand

the block-diagram corresponding to the case when the outputs are the joint positions and velocities, that is,

$$\boldsymbol{y} = \boldsymbol{y}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{f}) = \begin{bmatrix} \boldsymbol{q} \\ \dot{\boldsymbol{q}} \end{bmatrix}$$

while $\boldsymbol{\tau}$ is the input. In this case notice that for robots with n joints one has, in general, $2n$ outputs and n inputs.

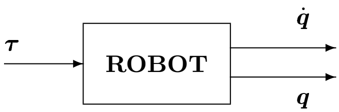

Figure 1.5. Input–output representation of a robot

1.2 Dynamic Model

At this stage, one determines the mathematical model which relates the input variables to the output variables. In general, such mathematical representation of the system is realized by ordinary differential equations. The system's mathematical model is obtained typically via one of the two following techniques.

- *Analytical*: this procedure is based on physical laws of the system's motion. This methodology has the advantage of yielding a mathematical model as precise as is wanted.
- *Experimental*: this procedure requires a certain amount of experimental data collected from the system itself. Typically one examines the system's behavior under specific input signals. The model so obtained is in general more imprecise than the analytic model since it largely depends on the inputs and the operating point[1]. However, in many cases it has the advantage of being much easier and quicker to obtain.

On certain occasions, at this stage one proceeds to a simplification of the system model to be controlled in order to design a relatively simple controller. Nevertheless, depending on the degree of simplification, this may yield malfunctioning of the overall controlled system due to potentially neglected physical phenomena. The ability of a control system to cope with errors due to neglected dynamics is commonly referred to as *robustness*. Thus, one typically is interested in designing robust controllers.

In other situations, after the modeling stage one performs the *parametric identification*. The objective of this task is to obtain the numerical values of different physical parameters or quantities involved in the dynamic model. The identification may be performed via techniques that require the measurement of inputs and outputs to the controlled system.

The dynamic model of robot manipulators is typically derived in the analytic form, that is, using the laws of physics. Due to the mechanical nature of robot manipulators, the laws of physics involved are basically the laws of mechanics.

On the other hand, from a dynamical systems viewpoint, an n-DOF system may be considered as a *multivariable nonlinear* system. The term "multivariable" denotes the fact that the system has multiple (*e.g.* n) inputs (the forces and torques $\boldsymbol{\tau}$ applied to the joints by the electromechanical, hydraulic or pneumatic actuators) and, multiple ($2n$) state variables typically associated to the n positions $\boldsymbol{q}$, and n joint velocities $\dot{\boldsymbol{q}}$. In Figure 1.5 we depict the corresponding block-diagram assuming that the state variables also correspond to the outputs. The topic of robot dynamics is presented in Chapter 3. In Chapter 5 we provide the specific dynamic model of a two-DOF prototype of a robot manipulator that we use to illustrate through examples, the performance of the controllers studied in the succeeding chapters. Readers interested in the aspects of dynamics are invited to see the references listed on page 16.

As was mentioned earlier, the dynamic models of robot manipulators are in general characterized by ordinary nonlinear and nonautonomous[2] differential equations. This fact limits considerably the use of control techniques

[1] That is the working regime.
[2] That is, they depend on the state variables and time. See Chapter 2.

tailored for linear systems, in robot control. In view of this and the present requirements of precision and rapidity of robot motion it has become necessary to use increasingly sophisticated control techniques. This class of control systems may include nonlinear and adaptive controllers.

1.3 Control Specifications

During this last stage one proceeds to dictate the desired characteristics for the control system through the definition of control objectives such as:

- stability;
- regulation (position control);
- trajectory tracking (motion control);
- optimization.

The most important property in a control system, in general, is *stability.* This fundamental concept from control theory basically consists in the property of a system to go on working at a regime or *closely* to it *for ever.*

Two techniques of analysis are typically used in the analytical study of the stability of controlled robots. The first is based on the so-called *Lyapunov* stability theory. The second is the so-called *input–output* stability theory. Both techniques are complementary in the sense that the interest in Lyapunov theory is the study of stability of the system using a *state* variables description, while in the second one, we are interested in the stability of the system from an input–output perspective. In this text we concentrate our attention on Lyapunov stability in the development and analysis of controllers. The foundations of Lyapunov theory are presented in the Chapter 2.

In accordance with the adopted definition of a robot manipulator's output $\boldsymbol{y}$, the control objectives related to *regulation* and *trajectory tracking* receive special names. In particular, in the case when the output $\boldsymbol{y}$ corresponds to the joint position $\boldsymbol{q}$ and velocity $\dot{\boldsymbol{q}}$, we refer to the control objectives as "*position* control in joint coordinates" and "*motion* control in joint coordinates" respectively. Or we may simply say "position" and "motion" control respectively. The relevance of these problems motivates a more detailed discussion which is presented next.

1.4 Motion Control of Robot Manipulators

The simplest way to specify the movement of a manipulator is the so-called "point-to-point" method. This methodology consists in determining a series of points in the manipulator's workspace, which the end-effector is required to pass through (*cf.* Figure 1.6). Thus, the position control problem consists in making the end-effector go to a specified point regardless of the trajectory followed from its initial configuration.

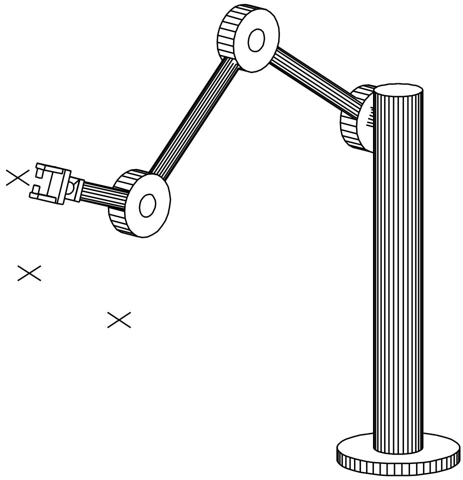

Figure 1.6. Point-to-point motion specification

A more general way to specify a robot's motion is via the so-called (continuous) trajectory. In this case, a (continuous) curve, or path in the state space and parameterized in time, is available to achieve a desired task. Then, the *motion* control problem consists in making the end-effector follow this trajectory as closely as possible (*cf.* Figure 1.7). This control problem, whose study is our central objective, is also referred to as trajectory tracking control.

Let us briefly recapitulate a simple formulation of robot control which, as a matter of fact, is a particular case of motion control; that is, the position control problem. In this formulation the specified trajectory is simply a point in the workspace (which may be translated under appropriate conditions into a point in the joint space). The position control problem consists in driving the manipulator's end-effector (resp. the joint variables) to the desired position, regardless of the initial posture.

The topic of motion control may in its turn, be fitted in the more general framework of the so-called *robot navigation.* The robot navigation problem consists in solving, in one single step, the following subproblems:

- path planning;
- trajectory generation;
- control design.

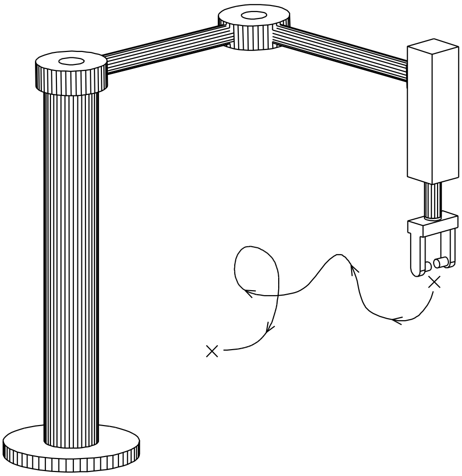

Figure 1.7. Trajectory motion specification

Path planning consists in determining a curve in the state space, connecting the initial and final desired posture of the end-effector, while avoiding any obstacle. Trajectory generation consists in parameterizing in time the so-obtained curve during the path planning. The resulting time-parameterized trajectory which is commonly called the *reference* trajectory, is obtained primarily in terms of the coordinates in the workspace. Then, following the so-called method of *inverse kinematics* one may obtain a time-parameterized trajectory for the joint coordinates. The control design consists in solving the control problem mentioned above.

The main interest of this textbook is the study of motion controllers and more particularly, the analysis of their inherent stability in the sense of Lyapunov. Therefore, we assume that the problems of path planning and trajectory generation are previously solved.

The dynamic models of robot manipulators possess parameters which depend on physical quantities such as the mass of the objects possibly held by the end-effector. This mass is typically unknown, which means that the values of these parameters are unknown. The problem of controlling systems with unknown parameters is the main objective of the *adaptive* controllers. These owe their name to the addition of an adaptation law which updates on-line, an estimate of the unknown parameters to be used in the control law. This motivates the study of adaptive control techniques applied to robot control. In the past two decades a large body of literature has been devoted to the adaptive control of manipulators. This problem is examined in Chapters 15 and 16.

We must mention that in view of the scope and audience of the present textbook, we have excluded some control techniques whose use in robot motion control is supported by a large number of publications contributing both theoretical and experimental achievements. Among such strategies we mention the so-called passivity-based control, variable-structure control, learning control, fuzzy control and neural-networks-based. These topics, which demand a deeper knowledge of control and stability theory, may make part of a second course on robot control.

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Robot dynamics is thoroughly discussed in Spong, Vidyasagar (1989) and Sciavicco, Siciliano (2000).

To read more on the topics of force control, impedance control and hybrid motion/force see among others, the texts of Asada, Slotine (1986), Craig (1989), Spong, Vidyasagar (1989), and Sciavicco, Siciliano (2000), previously cited, and the book

- Natale C., 2003, *"Interaction control of robot manipulators"*, Springer, Germany.
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Aspects of stability in the input–output framework (in particular, passivity-based control) are studied in the first part of the book

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In addition, we may mention the following classic texts.

- Raibert M., Craig J., 1981, *"Hybrid position/force control of manipulators"*, ASME Journal of Dynamic Systems, Measurement and Control, June.
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- United Nations/Economic Commission for Europe and International Federation of Robotics, 2001, *"World robotics 2001"*, United Nation Publication *sales No.* GV.E.01.0.16, ISBN 92–1–101043–8, ISSN 1020–1076, Printed at United Nations, Geneva, Switzerland.

We list next some of the most significant journals focused on robotics research.

- *Advanced Robotics*,
- *Autonomous Robots*,
- *IASTED International Journal of Robotics and Automation*
- *IEEE/ASME Transactions on Mechatronics*,
- *IEEE Transactions on Robotics and Automation*[3],
- *IEEE Transactions on Robotics*,
- *Journal of Intelligent and Robotic Systems*,
- *Journal of Robotic Systems*,
- *Mechatronics*,
- *The International Journal of Robotics Research*,
- *Robotica.*

Other journals, which in particular, provide a discussion forum on robot control are

- *ASME Journal of Dynamic Systems, Measurement and Control*,
- *Automatica*,
- *IEEE Transactions on Automatic Control*,
- *IEEE Transactions on Industrial Electronics*,
- *IEEE Transactions on Systems, Man, and Cybernetics*,
- *International Journal of Adaptive Control and Signal Processing*,
- *International Journal of Control*,
- *Systems and Control Letters.*

[3] Until June 2004 only.

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Control of Robot Manipulators in Joint Space
Kelly, R.; Santibáñez Davila, V.; Loría Perez, J.A.
2005, XXVI, 426 p. 110 illus. With online files/update.,
Softcover
ISBN: 978-1-85233-994-4