Introduction to Robotics

- 2.12 Lecture Notes -

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Chapter 1
Introduction

Many definitions have been suggested for what we call a *robot.* The word may conjure up various levels of technological sophistication, ranging from a simple material handling device to a humanoid. The image of robots varies widely with researchers, engineers, and robot manufacturers. However, it is widely accepted that today's robots used in industries originated in the invention of a programmed material handling device by George C. Devol. In 1954, Devol filed a U.S. patent for a new machine for part transfer, and he claimed the basic concept of *teach-in/playback* to control the device. This scheme is now extensively used in most of today's industrial robots.

1.1 Era of Industrial Robots

Devol's industrial robots have their origins in two preceding technologies: *numerical control* for machine tools, and *remote manipulation.* Numerical control is a scheme to generate control actions based on stored data. Stored data may include coordinate data of points to which the machine is to be moved, clock signals to start and stop operations, and logical statements for branching control sequences. The whole sequence of operations and its variations are prescribed and stored in a form of memory, so that different tasks can be performed without requiring major hardware changes. Modern manufacturing systems must produce a variety of products in small batches, rather than a large number of the same products for an extended period of time, and frequent changes of product models and production schedules require *flexibility* in the manufacturing system. The transfer line approach, which is most effective for mass production, is not appropriate when such flexibility is needed (Figure 1-1). When a major product change is required, a special-purpose production line becomes useless and often ends up being abandoned, despite the large capital investment it originally involved. Flexible automation has been a central

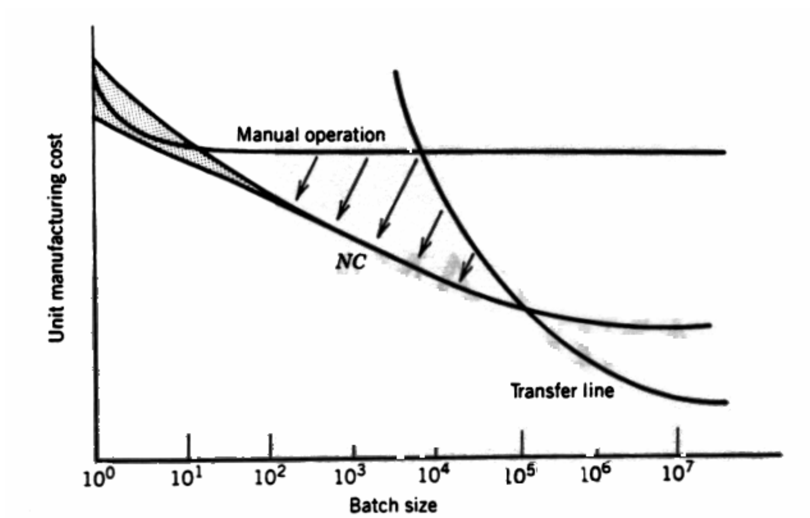
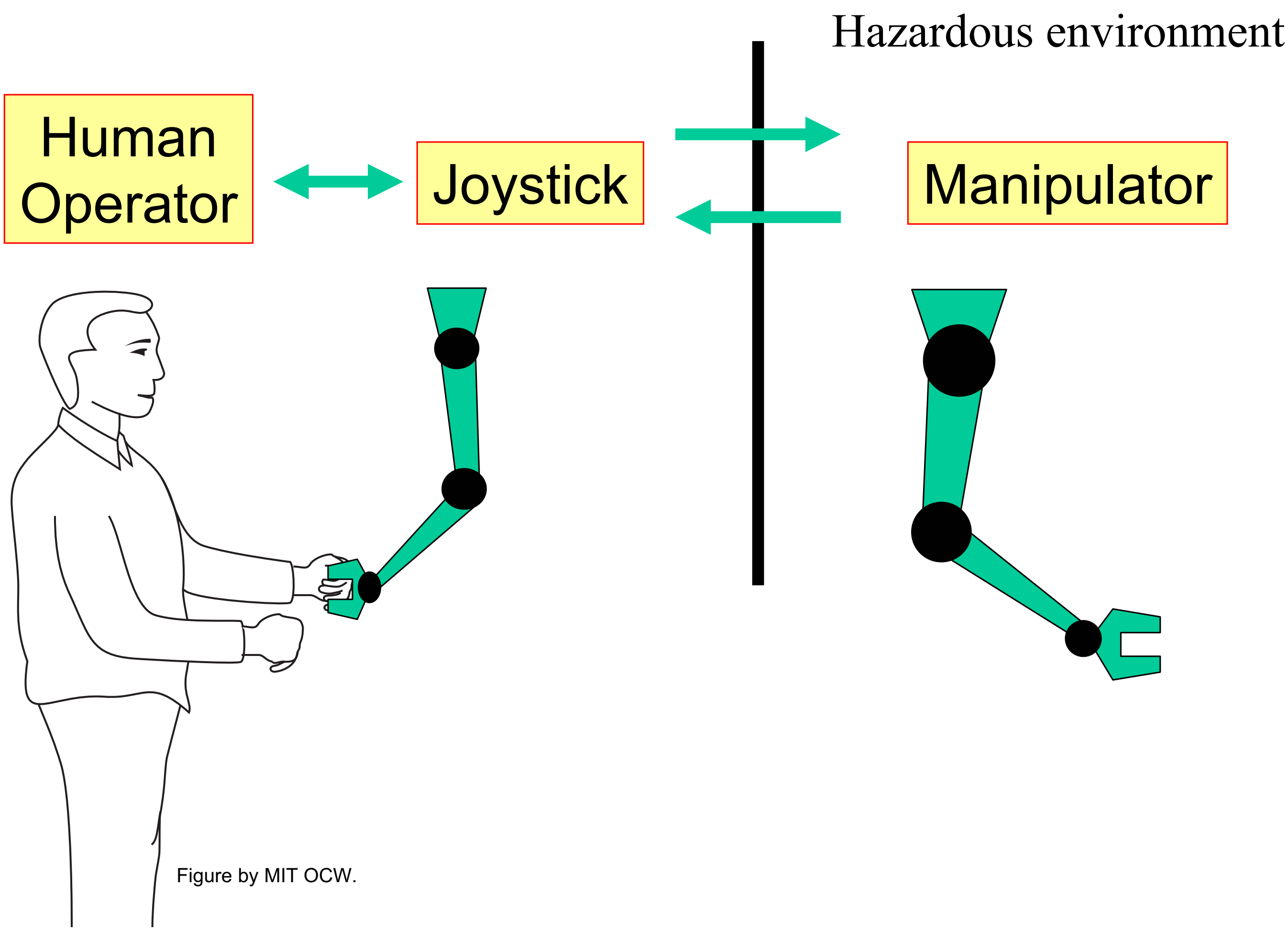


Figure 1-1 General trend of manufacturing cost vs. batch size

issue in manufacturing innovation for a few decades, and numerical control has played a central role in increasing system flexibility. Contemporary industrial robots are programmable machines that can perform different operations by simply modifying stored data, a feature that has evolved from the application of numerical control.

Another origin of today's industrial robots can be found in remote manipulators. A remote manipulator is a device that performs a task at a distance. It can be used in environments that human workers cannot easily or safely access, e.g. for handling radio-active materials, or in some deep sea and space applications. The first *master-slave manipulator* system was developed by 1948. The concept involves an electrically powered mechanical arm installed at the operation site, and a control joystick of geometry similar to that of the mechanical arm (Figure 1-2). The joystick has position transducers at individual joints that measure the motion of the human operator as he moves the tip of the joystick. Thus the operator's motion is transformed into electrical signals, which are transmitted to the mechanical arm and cause the same motion as the one that the human operator performed. The joystick that the operator handles is called the *master* manipulator, while the mechanical arm is called the *slave* manipulator, since its motion is ideally the replica of the operator's commanded motion. A master-slave manipulator has typically six degrees of freedom to allow the gripper to locate an object at an arbitrary position and orientation. Most joints are revolute, and the whole mechanical construction is similar to that of the human arm. This analogy with the human arm results from the need of replicating human motions. Further, this structure allows dexterous motions in a wide range of workspaces, which is desirable for operations in modern manufacturing systems.



Contemporary industrial robots retain some similarity in geometry with both the human arm and remote manipulators. Further, their basic concepts have evolved from those of numerical control and remote manipulation. Thus a widely accepted definition of today's industrial robot is that of a numerically controlled manipulator, where the human operator and the master manipulator in the figure are replaced by a numerical controller.

Figure removed for copyright reasons.
See Figure 1-4 in Asada and Slotine, 1986.

Figure 1-3 White body assembly lines using spot welding robots

1.2 Creation of Robotics

The merge of numerical control and remote manipulation created a new field of engineering, and with it a number of scientific issues in design and control which are substantially different from those of the original technologies have emerged.

Robots are required to have much higher *mobility and dexterity* than traditional machine tools. They must be able to work in a large reachable range, access crowded places, handle a variety of workpieces, and perform flexible tasks. The high mobility and dexterity requirements result in the unique mechanical structure of robots, which parallels the human arm structure. This structure, however, significantly departs from traditional machine design. A robot mechanical structure is basically composed of cantilevered beams, forming a sequence of arm links connected by hinged joints. Such a structure has inherently poor mechanical stiffness and accuracy, hence is not appropriate for the heavy-duty, high-precision applications required of machine tools. Further, it also implies a serial sequence of servoed joints, whose errors accumulate along the linkage. In order to exploit the high mobility and dexterity uniquely featured by the serial linkage, these difficulties must be overcome by advanced design and control techniques.

The serial linkage geometry of manipulator arms is described by complex nonlinear equations. Effective analytical tools are necessary to understand the geometric and kinematic behavior of the manipulator, globally referred to as the manipulator *kinematics.* This represents an important and unique area of robotics research, since research in kinematics and design has traditionally focused upon single-input mechanisms with single actuators moving at constant speeds, while robots are multi-input spatial mechanisms which require more sophisticated analytical tools.

The *dynamic* behavior of robot manipulators is also complex, since the dynamics of multi-input spatial linkages are highly coupled and nonlinear. The motion of each joint is significantly affected by the motions of all the other joints. The inertial load imposed at each joint varies widely depending on the configuration of the manipulator arm. Coriolis and centrifugal effects are prominent when the manipulator arm moves at high speeds. The kinematic and dynamic complexities create unique control problems that are not adequately handled by standard linear control techniques, and thus make effective *control system design* a critical issue in robotics.

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See http://www.adept.com

Figure 1-4 Adept Direct-Drive robot

Finally, robots are required to *interact* much more heavily with peripheral devices than traditional *numerically-controlled* machine tools. Machine tools are essentially self-contained systems that handle workpieces in well-defined locations. By contrast, the environment in which robots are used is often poorly structured, and effective means must be developed to identify the locations of the workpieces as well as to communicate to peripheral devices and other machines in a coordinated fashion. Robots are also critically different from master-slave manipulators, in that they are *autonomous* systems. Master-slave manipulators are essentially manually controlled

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Robot hand holding lightbulb - http://www.dlr.de/rm/en/Desktopdefault.aspx/tabid-426/569_read-76/

Figure 1-5 Dexterous fingers

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See http://menzelphoto.peripix.com/viewdetails/item/313/size/300/3/
'Also published Menzel, Peter, and Faith D'Aluisio. *Robo Sapiens: Evolution of a New Species*. Cambridge, MA: MIT Press, 2001, p. 176.'

Figure 1-6 Medical robots for minimally invasive surgery

systems, where the human operator takes the decisions and applies control actions. The operator interprets a given task, finds an appropriate strategy to accomplish the task, and plans the procedure of operations. He/she devises an effective way of achieving the goal on the basis of his/her experience and knowledge about the task. His/her decisions are then transferred to the slave manipulator through the joystick. The resultant motion of the slave manipulator is monitored by the operator, and necessary adjustments or modifications of control actions are provided when the resultant motion is not adequate, or when unexpected events occur during the operation. The human operator is, therefore, an essential part of the control loop. When the operator is eliminated from the control system, all the planning and control commands must be generated by the machine itself. The detailed procedure of operations must be set up in advance, and each step of motion command must be generated and coded in an appropriate form so that the robot can interpret it and execute it accurately. Effective means to store the commands and manage the data file are also needed . Thus, *programming and command generation* are critical issues in robotics. In addition, the robot must be able to fully monitor its own motion. In order to adapt to disturbances and unpredictable changes in the work environment, the robot needs a variety of *sensors*, so as to obtain information both about the environment (using *external* sensors, such as cameras or touch sensors) and about itself (using *internal* sensors, such as joint encoders or joint torque sensors). Effective sensor-based strategies that incorporate this information require advanced control algorithms. But they also imply a detailed understanding of the task.

1.3. Manipulation and Dexterity

Contemporary industrial needs drive the applications of robots to ever more advanced tasks. Robots are required to perform highly skilled jobs with minimum human assistance or intervention. To extend the applications and abilities of robots, it becomes important to develop a sound understanding of the *tasks* themselves.

In order to devise appropriate arm mechanisms and to develop effective control algorithms, we need to precisely understand how a given task should be accomplished and what sort of motions the robot should be able to achieve. To perform an assembly operation, for example, we need to know how to guide the assembly part to the desired location, mate it with another part, and secure it in an appropriate way. In a grinding operation, the robot must properly position the grinding wheel while accommodating the contact force. We need to analyze the grinding process itself in order to generate appropriate force and motion commands.

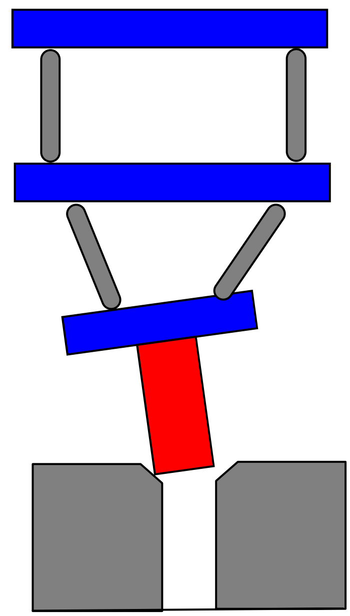

Figure 1-7 Remote-center compliance hand

A detailed understanding of the underlying principles and "know-how" involved in the task must be developed in order to use industrial robots effectively, while there is no such need for making control strategies *explicit* when the assembly and grinding operations are performed by a human worker. Human beings perform sophisticated manipulation tasks without being aware of the control principles involved. We have *trained* ourselves to be capable of skilled jobs, but in general we do not know what the acquired skills are exactly about. A sound and explicit understanding of manipulation operations, however, is essential for the long-term progress of robotics. This scientific aspect of manipulation has never been studied systematically before, and represents an emerging and important part of robotics research.

1.4 Locomotion and Navigation

Robotics has found a number of important application areas in broad fields beyond manufacturing automation. These range from space and under-water exploration, hazardous waste disposal, and environment monitoring to robotic surgery, rehabilitation, home robotics, and entertainment. Many of these applications entail some locomotive functionality so that the robot can freely move around in an unstructured environment. Most industrial robots sit on a manufacturing floor and perform tasks in a structured environment. In contrast, those robots for non-manufacturing applications must be able to move around on their own. See Figure 1-8.

Locomotion and navigation are increasingly important, as robots find challenging applications in the field. This opened up new research and development areas in robotics. Novel mechanisms are needed to allow robots to move through crowded areas, rough terrain, narrow channels, and even staircases. Various types of legged robots have been studied, since, unlike standard wheels, legs can negotiate with uneven floors and rough terrain. Among others, biped robots have been studied most extensively, resulting in the development of humanoids, as shown in Figure 1-9. Combining leg mechanisms with wheels has accomplished superior performance in both flexibility and efficiency. The Mars Rover prototype shown below has a rocker-buggy mechanism combined with advanced wheel drives in order to adapt itself to diverse terrain conditions. See Figure 1-10.

Figure 1-8 Automatically guided vehicle for meal delivery in hospitals

Figure 1-9 Honda’s P3 humanoid robot

Navigation is another critical functionality needed for mobile robots, in particular, for unstructured environment. Those robots are equipped with range sensors and vision system, and are capable of interpreting the data to locate themselves. Often the robot has a map of the environment, and uses it for estimating the location. Furthermore, based on the real-time data obtained in the field, the robot is capable of updating and augmenting the map, which is incomplete and uncertain in unstructured environment. As depicted in Figure 1-10, location estimation and map building are simultaneously executed in the advanced navigation system. Such Simultaneous Location and MApping (SLAM) is exactly what we human do in our daily life, and is an important functionality of intelligent robots.

The goal of robotics is thus two-fold: to extend our understanding about manipulation, locomotion, and other robotic behaviors and to develop engineering methodologies to actually perform desired tasks. The goal of this book is to provide entry-level readers and experienced engineers with fundamentals of understanding robotic tasks and intelligent behaviors as well as with enabling technologies needed for building and controlling robotic systems.

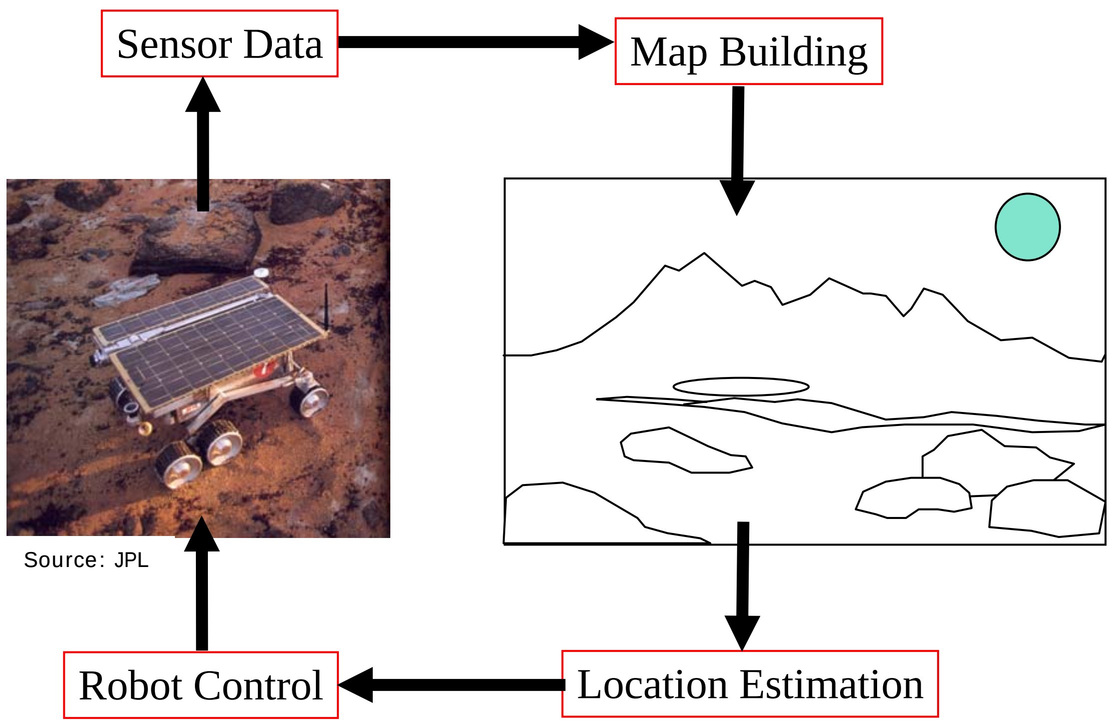

Figure 1-10 JPL's planetary exploration robot: an early version of the Mars Rover