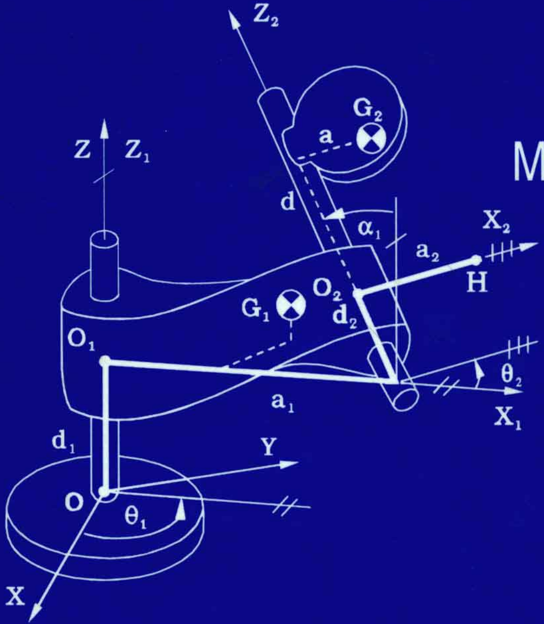
Fundamentals of Mechanics of Robotic Manipulation



by

MARCO CECCARELLI

MICROPROCESSOR-BASED AND INTELLIGENT SYSTEMS ENGINEERING

KLUWER ACADEMIC PUBLISHERS

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by

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Preface

This book has evolved from a course on Mechanics of Robots that the author has thought for over a dozen years at the University of Cassino at Cassino, Italy.
It is addressed mainly to graduate students in mechanical engineering although the course has also attracted students in electrical engineering. The purpose of the book consists of presenting robots and robotized systems in such a way that they can be used and designed for industrial and innovative non-industrial applications with no great efforts.
The content of the book has been kept at a fairly practical level with the aim to teach how to model, simulate, and operate robotic mechanical systems. The chapters have been written and organized in a way that they can be red even separately, so that they can be used separately for different courses and readers. However, many advanced concepts are briefly explained and their use is empathized with illustrative examples. Therefore, the book is directed not only to students but also to robot users both from practical and theoretical viewpoints. In fact, topics that are treated in the book have been selected as of current interest in the field of Robotics. Some of the material presented is based upon the author's own research in the field since the late 1980's.
In Chapter 1 an introductory overview of robots and Robotics is given by presenting basic characteristics and motivation for robot uses and by outlining a historical development. Chapter 1 outlines briefly the history and development that led to robots and robotized systems. The arguments are presented as a motivation for the interest on the applications of robots as well as for an in-depth study of the theoretical aspects. The technical evolution of automatic systems to robots is outlined by finally presenting the technical characteristics of a robot as a special automatic component. Indeed robots can be considered the most advanced automatic systems. With the aim to justify extensive use of robots an economic evaluation of using robots is presented and discussed. In addition, many other problems and aspects are outlined with the aim to give a wide view of the concerns related to the use of the robots not only in an industrial plant, but also in the human society. Thus, arguments from economy, psychology, and sociology are listed to give an account of all the problems that should be considered when using robots. However, the book concerns with technical aspects that are still addressing great attention even from research viewpoint. Thus, at the end of the chapter there is a list of forum where the technical aspects of Robotics are usually discussed. This information can be considered important even for further study of readers on the topics of this book and related arguments.
Chapter 2 deals with analysis and synthesis of manipulation by using men, automatic systems, or robots. The problem is attached in a way that any of the above-mentioned systems can apply the results of the study of a manipulation to give a rational flexible plan for a manipulative task. In particular, the aim of a flexible programming and design of a manipulation sequence is achieved by decomposing a manipulation into operations, phases, and elementary actions that have a decreasing content of

manipulative actions. A general procedure is outlined for analyzing manipulations as based on the above-mentioned decomposition. The procedure is formulated with no specific reference to robots, although the rest of the chapter describes its application with robots. Thus, the programming issue is discussed by referring to industrial robots and particularly to VAL-II language, which is used to describe peculiarities of grammar and syntax of a robot language. Several examples are illustrated and discussed by using teaching experiences and practical applications of industrial robots. The aim of describing many examples consists of presenting how a theoretical study of manipulation can be of great help for practical applications, even for a flexible programming of robotized solutions.

Chapter 3 is devoted to explain the behavior and operation of robots from Mechanics viewpoint with the aim to deduce formulations that are useful for analysis and design purposes. The arguments are attached in the frame of Mechanics of Robots, but the treatment is synthetic with the aim to deduce useful formulation even for simulation purpose on PC. Kinematics is approached by defining a model through HD (Hartenberg -Denavit) parameters. The position analysis is formulated by using Transformation Matrix (in homogenous coordinates), which is described from several viewpoints. The joint space and actuator spaces are illustrated and a simple example shows numerical details. A specific attention is addressed to workspace analysis, which is formulated in several algorithms. The position analysis is inverted to define the manipulator design problem. General formulations are outlined by using techniques deduced from the synthesis of mechanisms, but also an optimization problem is formulated and discussed. The path planning is approached starting from formulation of Inverse Kinematics. The two subjects are described as strongly related to each other, although some specific formulations are deduced for each of them. The singularity problem is illustrated by using the Jacobian analysis. The Jacobian matrix of a manipulator is defined and algorithms are outlined for its evaluation. Addressing to velocity and acceleration analysis with recursive algorithms completes the Kinematics, which makes use of the Transformation Matrix. The static behavior of a manipulator is studied through a suitable model, which is described with specific attention and comments. Then, the static equilibrium is formulated by using the traditional approach with D'Alembert Principle. An example is included to show closed-form expressions as well as to discuss numerical issues. The static model is further completed with inertia characteristics in order to study the Dynamics of a manipulator. The two fundamental approaches of Newton-Euler Equations and Lagrange Formulation are treated to give the equations of motion and constraints forces. Examples are used to illustrate and discuss details of the algorithms and numerical problems of simulation. Specific sections are devoted to discuss other main characteristics of a manipulator: repeatability, precision, and stiffness. Formulation and comments are deduced with the aim to help the understanding of their effect on the efficiency of a robot. The end of the chapter is devoted to introduce the Mechanics of parallel manipulators, mainly referring to a prototype CaPaMan (Cassino Parallel Manipulator) that has been designed and built at Laboratory of Robotics and Mechatronics in Cassino. Synthetically the fundamentals of the Mechanics of parallel manipulators is outlined similarly to the previous sections for serial manipulators with the aim to show differences but analogies in the formulation and behavior.

Chapter 4 deals with problems of grasping as an important aspect for a manipulator component and manipulative task. Gripping devices are reviewed together with their fundamental characteristics in order to give a view of existent variety. However, the attention is focused on two-finger grippers, which are justified and motivated by considering the model of grasp and relevant Statistics for two-finger grasp applications. Thus, the two-finger grasp is studied in depth by means of models and formulations, which are also useful for design algorithms and force control purposes. The design issue is treated by looking at the mechanisms that are used in grippers and formulating the design problem, even as an optimization problem when suitable performance indices are defined. The grasp force control is described by referring to the Mechatronics operation and design of a gripper. In particular, different control schemes are described by using electropneumatic systems, since they are the most used in industrial applications. Some laboratory experiences are described and discussed as example of designing, operating, practicing with a gripping system.

The Index consists of an alphabetically ordered list of subjects treated in the book with the indication of the corresponding pages.

Bibliography consists of a list of main books in the field of Robotics, and specifically on Mechanics of Robots with the aim to give further sources of reading and references of different approaches. In the book there is not any reference to Bibliography. Bibliography has been limited to few significant books, although the literature on Robotics and mechanical aspects of Robots is very rich. However, main sources have been indicated in Chapter 1 as publications in Journals and Conference Proceedings in which readers can also find new material.

The author would like to acknowledge the collaboration with his former professor Adalberto Vinciguerra at University "La Sapienza" of Rome. The author is thankful also to his pupils and now colleagues Erika Ottaviano, Chiara Lanni, Giuseppe Carbone, and to professor Giorgio Figliolini for the collaboration at LARM: Laboratory of Robotics and Mechatronics. The author will thank also the former students who taught to the author how to teach and transmit his theoretical and practical experience on robotic systems to them within the limited period of a semester. Also acknowledged is the professional assistance by the staff of Kluwer Academic Publishers, Dordrecht (The Netherlands), especially by Miss Nathalie Jacobs.

The author is grateful to his wife Brunella, daughters Elisa and Sofia, and son Raffaele for their patience and comprehension over the many years during which this book was developed and written.

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Cassino, Italy
December 2003

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Chapter 1:
Introduction to Automation and Robotics

1.1 Automatic systems and robots

Robots can be considered as the most advanced automatic systems and robotics, as a technique and scientific discipline, can be considered as the evolution of automation with interdisciplinary integration with other technological fields.
An automatic system can be defined as a system which is able to repeat specific operations generally with a low degree of intellectual and manipulative levels, but that can be easily programmed in agreement with demands of productivity.
It is worthy of note that an automatic system is generally able to perform one operation for which its mechanical structure has been designed. Aspects of flexibility depend on the possibility of reprogramming the control unit, which is generally able only to modify the time sequence of the designed operations. Therefore, an automatic system of industrial type can be thought of as composed of two parts:
- hardware with mechanical, electrical, pneumatic, and hydraulic components that provide the mechanical capability to perform an *a priori*-determined operation of movement and/or manipulation;
- control and operation counterpart with electronic components and software that provide the capability of autonomy and flexibility to the working of the system.

The two parts are essential in an automatic system and are integrated in the sense that their design and operation must be considered as a unique goal in order to obtain and operate an automatic system with the best performances. Therefore, an automatic system in which the hardware part is preponderant cannot have a suitable flexibility for a flexible production in agreement with the demands of productivity and market. In some cases these limited solutions are still required from productivity , when the product of a massive production is absorbed from the market with certain regularity during a period of time longer than the amortization time of the automatic system. Those systems with low flexibility are generally denominated as 'rigid automatic systems'. In Fig. 1.1 the variety of production systems is represented as a function of the productivity level.
Automatic systems are often designed with the aim of having the possibility of an easy updating of their structure and operation with the purpose of being adjusted more quickly to the mutable demands of production and design of products. These very flexible systems are denominated as 'flexible automatic systems'.
In addition, it is worthy of note that a system with only the mechanical counterpart, although versatile, cannot be considered an automatic system since the updating of its operation is not obtained by means of control units. Such a system can be properly reprogrammed, but it requires the manual action of one or more human operators to change some components of the machinery or their running. Therefore, these systems can be properly named as machinery or mechanical systems.

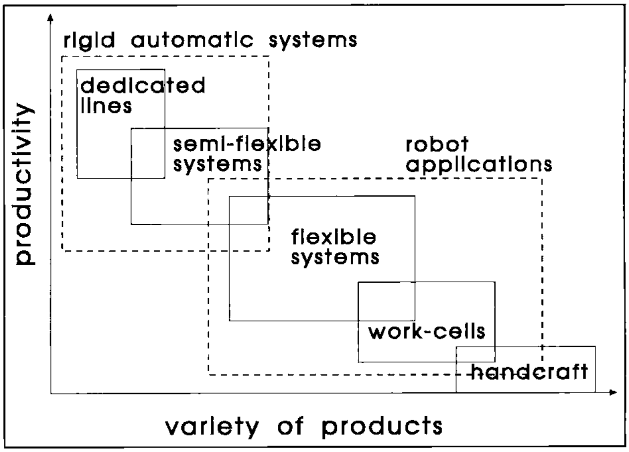

Fig. 1.1: Variety of automatic and robotized systems as functions of productivity level and product demand.

Similarly, control systems cannot be considered as automatic systems, since they are not able to perform mechanical tasks, although they can be provided with a high level of flexibility in terms of re-programmability and memory capability. Therefore these systems can be properly named as control units or electrical–electronic–informatics systems.

However, an automatic system is designed and built by using a suitable combination and integration of mechanical systems and control units. Indeed, the success and engineering application of automatic systems strongly depends on the practical integration of the above-mentioned counterparts.

A robot can be defined as a system which is able to perform several manipulative tasks with objects, tools, and even its extremity (end-effector) with the capability of being re-programmed for several types of operations. There is an integration of mechanical and control counterparts, but it even includes additional equipment and components, concerned with sensorial capabilities and artificial intelligence. Therefore, the simultaneous operation and design integration of all the above-mentioned systems will provide a robotic system, as illustrated in Fig. 1.2.

In fact, more than in automatic systems, robots can be characterized as having simultaneously mechanical and re-programming capabilities. The mechanical capability is concerned with versatile characteristics in manipulative tasks due to the mechanical counterparts, and re-programming capabilities concerned with flexible characteristics in control abilities due to the electric-electronics-informatics counterparts. Therefore, a robot can be considered as a complex system that is composed of several systems and devices to give:

- mechanical capabilities (motion and force);
- sensorial capabilities (similar to human beings and/or specific others);
- intellectual capabilities (for control, decision, and memory).

Initially, industrial robots were developed in order to facilitate industrial processes by substituting human operators in dangerous and repetitive operations, and in unhealthy environments. Today, additional needs motivate further use of robots, even from pure technical viewpoints, such as productivity increase and product quality improvements. Thus, the first robots have been evolved to complex systems with additional capabilities.

Nevertheless, referring to Fig. 1.2, an industrial robot can be thought of as composed of:

- a mechanical system or manipulator arm (mechanical structure), whose purpose consists of performing manipulative operation and/or interactions with the environment;
- sensorial equipment (internal and external sensors) that is inside or outside the mechanical system, and whose aim is to obtain information on the robot state and scenario, which is in the robot area;
- a control unit (controller), which provides elaboration of the information from the sensorial equipment for the regulation of the overall systems and gives the actuation signals for the robot operation and execution of desired tasks;
- a power unit, which provides the required energy for the system and its suitable transformation in nature and magnitude as required for the robot components;
- computer facilities, which are required to enlarge the computation capability of the control unit and even to provide the capability of artificial intelligence.

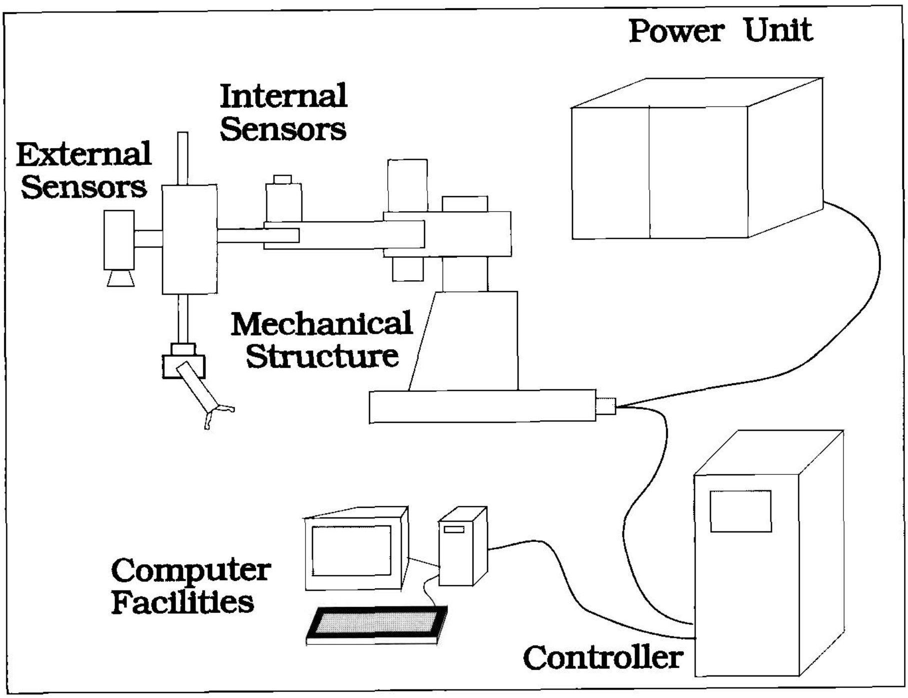

Fig. 1.2: Components of an industrial robot.

Thus, the above-mentioned combination of sub-systems gives the three fundamental simultaneous attitudes to a robot, i.e. mechanical action, data elaboration, and re-programmability.
Consequently, the fundamental capability of robotic systems can be recognized in:
- mechanical versatility;
- re-programmability.

Mechanical versatility of a robot can be understood as the capability to perform a variety of tasks because of the kinematic and mechanical design of its manipulator arm.
Re-programmability of a robot can be understood as the flexibility to perform a variety of task operations because of the capability of its controller and computer facilities.
These basic performances give a relevant flexibility for the execution of several different tasks in a similar or better way than human arms. In fact, nowadays robots are well-established equipment in industrial automation since they substitute human operators in operations and situations, which are:
- dangerous – for manipulative tasks and/or unhealthy environments;
- repetitive – with low-level cultural and technical content;
- tiresome – for manipulative tasks requiring energy greater than that provided by a human operator;
- difficult – for human operators.

In addition, the use of robots is well-established in industrial production since robots are:
- versatile, as they have the ability to operate in different situations;
- useful for unhealthy or limited environments, which can be dangerous or unfeasible for human operators.

Besides the above-mentioned motivations of technical nature, robots and robotic systems are currently used with the aim of:
- decreasing production costs, which can be related to a better use of the machinery;
- increasing productivity, with an increase of the operation velocity;
- enhancing product quality, in terms of constant characteristics and improved manufacturing;
- achieving flexible production as a capability of rapid adjustment of production to required changes in manufacturing.

The mechanical capability of a robot is due to the mechanical sub-system that generally is identified and denominated as the 'manipulator', since its aim is the manipulative task.
The term manipulation refers to several operations, which include:
- grasping and releasing of objects;
- interaction with the environment and/or with objects not related with the robot;
- movement and transportation of objects and/or robot extremity.

Consequently, the mechanical sub-system gives mechanical versatility to a robot through kinematic and dynamic capability during its operation. Manipulators can be classified according to the kinematic chain of their architectures as:
- serial manipulators, when they can be modeled as open kinematic chains in which the links are jointed successively by binary joints;

- parallel manipulators, when they can be modeled as closed kinematic chains in which the links are jointed to each other so that polygonal loops can be determined.

In addition, the kinematic chains of manipulators can be planar or spatial depending on which space they operate. Most industrial robotic manipulators are of the serial type, although recently parallel manipulators have aroused great interest and are even applied in industrial applications.

In general, in order to perform similar manipulative tasks as human operators, a manipulator is composed of the following mechanical sub-systems:

- an arm, which is devoted to performing large movements, mainly as translations;
- a wrist, whose aim is to orientate the extremity;
- an end-effector, which is the manipulator extremity that interacts with the environment.

Several different architectures have been designed for each of the above-mentioned manipulator sub-systems as a function of required specific capabilities and characteristics of specific mechanical designs. It is worthy of note that although the mechanical design of a manipulator is based on common mechanical components, such as all kinds of transmissions, the peculiarity of a robot design and operation requires advanced design of those components in terms of materials, dimensions, and designs because of the need for extreme lightness, compactness, and reliability.

The sensing capability of a robot is obtained by using sensors suitable for knowing the status of the robot itself and surrounding environment. The sensors for robot status are of fundamental importance since they allow the regulation of the operation of the manipulator. Therefore, they are usually installed on the manipulator itself with the aim of monitoring basic characteristics of manipulations, such as position, velocity, and force. Additionally, an industrial robot can be equipped with specific and/or advanced sensors, which give human-like or better sensing capability. Therefore, a great variety of sensors can be used, to which the reader is suggested to refer to in specific literature.

The control unit is of fundamental importance since it gives capability for autonomous and intelligent operation to the robot and it performs the following aims:

- regulation of the manipulator motion as a function of current and desired values of main kinematic and dynamic variables by means of suitable computations and programming;
- acquisition and elaboration of sensor signals from the manipulator and surrounding environment;
- capability of computation and memory, which is needed for the above-mentioned purposes and robot re-programmability.

In particular, an intelligence capability has been added to some robotic systems concerned mainly with decision capability and memory of past experiences by using the means and techniques of expert systems and artificial intelligence. Nevertheless, most of the current industrial robots have no intelligent capability since the control unit properly operates for the given tasks within industrial environments. The control systems that are used in robots can be classified as:

- electro-mechanical sequencer units with end-stroke stops; units with pneumatic logic; electronic units with logic; PLC (Programmable Logic Controller) units;
- micro-processors;

- minicomputers;
- computers.

Indeed, nowadays industrial robots are usually equipped with minicomputers, since the evolution of low-cost PCs has determined the wide use of PCs in robotics so that sequencers, which are going to be restricted to PLC units only, will be used mainly in rigid automation or low-flexible systems.

Since robots can be considered complex systems both in design and operation even within work-cells, it is of fundamental importance and convenience to have the possibility to simulate robot operation and even the overall robotic systems. Using numerical methods and/or experimental tests even with laboratory prototypes can simulate robots. Therefore, an expert in automation and robotics should be aware of and be able to work with techniques and methodologies which are useful in designing and running the above-mentioned simulations.

1.2 Evolution and applications of robots

It is well known that the word 'robot' was coined by Karel Capek in 1921 for a theater play dealing with cybernetic workers, who/which replace humans in heavy work.

Indeed, even today the word 'robot' has a wide meaning that includes any system that can operate autonomously for a given class of tasks. Sometimes intelligent capability is included as a fundamental property of a robot, as shown in many works of fiction and movies, although many current robots, mostly in industrial applications, are far from being intelligent machines.

From a technical viewpoint a unique definition of a robot has taken time to be universally accepted. In 1988 the International Standard Organization (ISO) states: "An industrial robot is an automatic, servo-controlled, freely programmable, multipurpose manipulator, with several axes, for the handling of work pieces, tools or special devices. Variably programmed operations make possible the execution of a multiplicity of tasks".

However, different definitions are still used. In 1991 the International Federation for the Promotion of Mechanisms and Machine Science (formerly the International Federation for the Theory of Machines and Mechanisms) (IFToMM)gives its own definitions. Robot is defined as "Mechanical system under automatic control that performs operations such as handling and locomotion"; and manipulator is defined as "Device for gripping and controlled movements of objects".

Even roboticists still use their own definition for robots to emphasize some peculiarities. For example in 2001 from the IEEE (the Institute of Electrical and Electronics Engineers) community one can find the statement: "a robot is a machine constructed as an assemblage of joined links so that they can be articulated into desired positions by a programmable controller and precision actuators to perform a variety of tasks".

Different meanings for robots are still persistent from nation to nation, from technical field to technical field, and from application to application.

Nevertheless, a robot or robotic system can be recognized when it has three main characteristics: mechanical versatility, re-programming capacity, and intelligent capability.

However, the word 'automaton' can still be conveniently used in many cases, when the semantic meaning is fully understood from the originating word. The word means "something having the power of spontaneous motion" and it comes from the Greek word 'automaton', which is composed of the terms 'auto' and 'matos' that have the meaning of 'self' and 'moving/acting', respectively.

Thus, the term 'robot' can be addressed to systems, whose meaning and characteristics are those reported in the above-mentioned modern definitions for robots. The automaton/automata term can still be used for systems that do not correspond fully to the current robot concept, but can still show autonomous operation capability.

Therefore, one should properly name as robots only those systems that have been designed in the last five decades. Nevertheless, those concepts can be recognized in many systems of the past and one can still use the word 'robot' in a broad sense when she/he refers to historical solutions.

The idea of a substitute/help for men in heavy/unpleasant work can be found since the beginning of humanity. Thus, tools and machines were conceived, built, and used as intermediate solutions with increasing performance over time. Substitutes for manpower were also considered in Antiquity. Slaves were the first efficient 'intelligent machinery' solutions! but artificial solutions were also considered, mainly from theoretical viewpoints.

In VIIIth century B.C., in the 18th book of The Iliad, Homer describes maidservants that are built by Vulcan for the service of the Gods: they are mobile by using wheels, are nicely human shaped, are able to speak and with some intelligence. Homer described several other intriguing machines provided with automatic operation and even artificial intelligence. They show that in Homeric times the idea of a robot (properly 'automaton') for doing practical work, even for manufacturing purposes, was not considered altogether impossible, but within human reach.

However, in Homer's poetry the robots are mainly used to astonish the reader. This aim, indeed, was quite common in the Greek Theater that made use regularly of automatons and automatic machines to some extent. Emblematic are those that are mentioned in the plays by Aeschylus, and later by Aristophan.

The theatric machines were basically large mechanisms consisting of booms, wheels, and ropes that could raise weights/persons and even in some cases move back and forth quickly to simulate space motions. Unfortunately, none of the Theater machines still exist since they were made of perishable materials. However, one can find several references to these theatric machines in the Greek plays and even in vase paintings.

The engineering of Theater machines was persistent in Antiquity in Greece and in the Roman Empire. The Greeks reached heights in knowledge even in technical fields. The emblematic example is the School of Alexandria in Egypt where since the IIIrd century B.C. there was intense activity in teaching and also research on automatic devices. A brilliant example is the work by Heron of Alexandria who, in particular, treated in depth pneumatics and automatic mechanisms for several applications. The *Treatise on Pneumatics* by Heron was a masterpiece for designing automatic machines not only in Antiquity, but it was rediscovered and also used during the Renaissance.

Greek culture evolved and circulated as combined with Roman technology. The

Romans also further developed a technical culture in other fields, such as civil structures (roads, buildings, bridges, etc.) and in military applications (war machines, defense structures, etc.). They conceived and built several machines that could help humans in the work, although they made extensive use of slaves as perfect robots, since sometimes slaves were used as machinery without any moral attention. However, Roman engineers enhanced the mechanical design and automation.

A brilliant example is Vitruvius, who lived in 1st century B. C. and wrote an encyclopedic treatise 'De Architectura' that was rediscovered and used during the Renaissance. In the liber X Vitruvius treats in detail mechanisms and mechanical design of machines.

But technical evolution in machine design was important not only in the western world.

For example, in China the culture reached heights that also needed mature technology. In the field of automation Chinese designers developed brilliant solutions.

A very significant example is the Wooden Cow that was used for transportation purposes of heavy loads by using a one degree of freedom (d.o.f.) walking machine, as shown in Fig. 1.3.

Another very significant example can be selected from the Arabic world which achieved great technical designs during the Middle Ages.

An example is reported in Fig. 1.4, where an intriguing mechanisms is shown to operate as an automaton that provides water for washing hands and then a towel for drying hands, and finally it goes back to a start configuration. The mechanical design of the

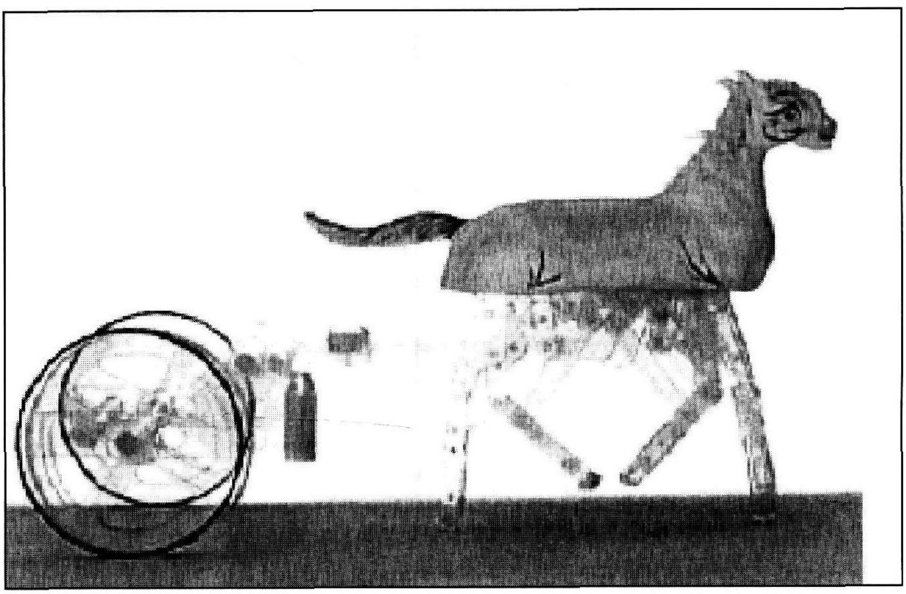

Fig. 1.3: A modern reconstruction of the Chinese Wooden Cow that was designed and built in Vth century B.C. (from the Ancient Chinese Machines Foundation at National Cheng Kung University in Tainan).