Robotics

State of the Art and Future Trends

Giovanni Legnani
Irene Fassi
Editors

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ROBOTICS

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GIOVANNI LEGNANI
AND
IRENE FASSI
EDITORS

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PREFACE

Robotics, although being a relatively new discipline, has however reached a good maturity in many domains, both from the research and market point of view. Over the years, many books, textbooks, handbooks have been published, covering all different aspects of this challenging field. So, why another book on robotics?

Of course because robotics is in great evolution and evolution must be studied, and understood to be governed.

This book holds a very exciting title. We imagined to start with a critical analysis of the state of the market, to understand which type of robots are present, which operations they perform, which are the unresolved requests of the market. Another important aspect is the analysis of the more promising research fields and the results which are "ready" in the labs and are waiting for a successful industrialization and commercialization process.

Many people would think that such a challenging analysis could be performed only by a set of high qualified experts with a strong experience. And the result would be one among the many other books in the field of robotics. We decided to afford the challenge using a different approach based on bright promising investigators maybe with less experience but a lot of enthusiasm.

Each Chapter is structured with a first section addressing the fundamentals (a brief review of the state of the art and current practices on the assigned topic) and a second part discussing an interesting application.

The book is opened by a Chapter which reviews the current status of the industrial automation. The global market and the different application fields are analyzed both from a dimension point of view as well as available technologies. This Chapter reviews the general robot structures and highlights the manipulator typologies dominating the scene (anthropomorphic, SCARA, delta, cartesian). However many different practical versions dedicated to specific fields (e.g. foundry, assembly, food, medical) have been developed to fulfill special requirements. The different versions differ for size, mechanical performances (payload, velocity, accuracy) as well as for external sensorization and programmability features. Intelligence and sensorization are important ingredients of many modern installations. The myth of a general purpose manipulator able to perform any task with success is a bit obfuscated by the necessity of high specialization in many fields.

While most of the installed industrial robots are serial, the only diffused exception being Delta type manipulators, the research on innovative kinematic structures is still active. Research from a mechanical point of view includes the modeling and the kinematics analysis of the manipulators. Chapter 2 and Chapter 3 address the kineto-static analysis and workspace optimization of various types of parallel manipulators with 3 and 4 degrees of freedom (dof).

The necessity of improving the dynamical performances of the manipulators calls for an extension of the classical analysis: kinematics cannot be restricted to position, velocity, and acceleration but it should be extended also to jerk. To better study this topic, an approach based on screw theory may be very successful and efficient, especially when dealing with parallel kinematic machines. Chapter 4 addresses the mobility analysis of 3 dof parallel manipulators using the screw theory, while Chapter 5 discusses the application of screw algebra to jerk analysis of 6 dof manipulators.

Chapter 6 aims at providing the fundamentals for dynamic modeling, analysis and system identification of parallel robots and proposes a model based identification method to identify the dynamic parameters value. This methodology can be applied also to serial manipulators. The necessity to improve the control performances of the manipulators in term of stability and path accuracy requires new tools. In some applications, standard PID controllers seem not adequate and several non conventional techniques have been proposed in the last decades. In Chapter 7, a controller based on fractional derivative is presented. Chapter 8 is devoted to "visual feedback" techniques, which allow controlling a robot by a vision system. The camera located on the manipulator analyzes a scene and commands the robot to reach a predefined pose with respect to a fixed or moving body. This is one of the most common modern techniques to give flexibility to a working cell.

An emerging research field deals with robots interacting with loosely structured environments. In the industrial foreground, manipulators and humans may share the same working space to cooperate in the execution of a task. This is the destruction of the traditional idea that human and robots should be kept separated for safety issues. Chapter 9 presents a new robotic system based on multiple sensors and human cooperation to gain more flexibility in various industrial tasks.

A strict interaction between human and robot is required also is the medical environment, where the use of robotic means is becoming every day more and more important. Chapter 10 and Chapter 11 provide the rationale for the use of robots in the rehabilitation field. The main issues in designing and implementing such systems are reviewed and two different applications based either on the customization of an industrial robot or on the designing of an exoskeleton for the upper limb rehabilitation, are presented.

Another challenging task is robotics at the micro-world. Chapter 12 reviews the main challenges in automating picking and precisely place of parts with dimensions of few micrometers and presents some interesting case studies.

Of course a single book cannot analyze all the modern robotic issues. A large encyclopedia would be necessary. But the present book can be considered like a balcony from which we can observe a wide panorama of some of the challenging robotic issues of today – an instrument to understand the place from where we came, where we are, where we are going.

Finally, we want to acknowledge the efforts of all the contributors, who answered promptly and patiently to all our requests and we wish that the readers will find interesting and fruitful hints for their future work. Enjoy the reading!

Irene Fassi, Giovanni Legnani

CONTENTS

In: Robotics: State of the Art and Future Trends
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Chapter 1

ROBOT IN INDUSTRIAL APPLICATIONS: STATE OF THE ART AND CURRENT TRENDS

L. Tirloni[1,*], I. Fassi[2,4,†] and G. Legnani[3,4,‡]

[1]REA Robotics s.r.l, Via Volta 35, 35030 Veggiano Padova, Italy
[2]Istituto Tecnologie Industriali ed Automazione, Consiglio Nazionale delle Ricerche
Via Bassini 15, 20131 Milano, Italy
[3]Università di Brescia, Dip. Ingegneria Meccanica e Automazione,
Via Branze 38, 25123 Brescia, Italy
[4]SIRI – Italian Robotic and Automation Association, Italy

Abstract

This Chapter aims at analyzing the state of the art in industrial robotics, in terms of successful industrial applications, from the perspective of robotic manufacturers and system integrators. It is worth to note that some of the solutions presented hereafter as innovative may be well known among the scientific community. However, due to many reasons, they only recently reached the market.

The idea is to highlight the gap between recent research results and industrial applications to stimulate the technology transfer from academia to common practice.

Firstly, the current market of industrial robotics will be analyzed and future trends discussed, in term of number and type of installed robots as well as in term of available technology. At the beginning, the paper presents official statistics updated to 2010. These statistics are derived from those collected by IFR (International Federation of Robotics) in cooperation with OECD and UNECE. The selected data describe the size of the market, the more consolidated applications and the new trends.

The second part of the chapter describes the robotic technology available on the market, in term of kinematical structure of the manipulators, programmability of robotized cells, and sensors to improve flexibility. The different robot typologies are reviewed with respect to the robot applications and commercially available models.

* E-mail address: lorenzo.tirloni@reagroup.it
† E-mail address: irene.fassi@itia.cnr.it
‡ E-mail address: giovanni.legnani@ing.unibs.it

The topics are discussed with several references to standard and innovative applications highlighting where technology transfer and/or some degree of innovation is still necessary.

1. Introduction

1.1 The Market

Nowadays robots are widely used in industrial applications, spanning from food to pharmaceutical to naval industry to perform either simple tasks, as loading/unloading of work-pieces on machine tools or more complex processes, such as assembly, soldering, painting, deburring, cutting. Figure 1 shows the distribution of industrial robots in the different sectors and their target application.

Major robot manufacturers are in Japan and Europe. Among them, the most important in term of volume of produced robots and product range are: Fanuc (J), Nachi (J), Kawasaki (J), Motoman (J), Toshiba (J), Panasonic (J), Denso (J), ABB (S), Kuka (D), Reiss (D), Staubli (CH), Hyundai (ROK), and Comau (I).

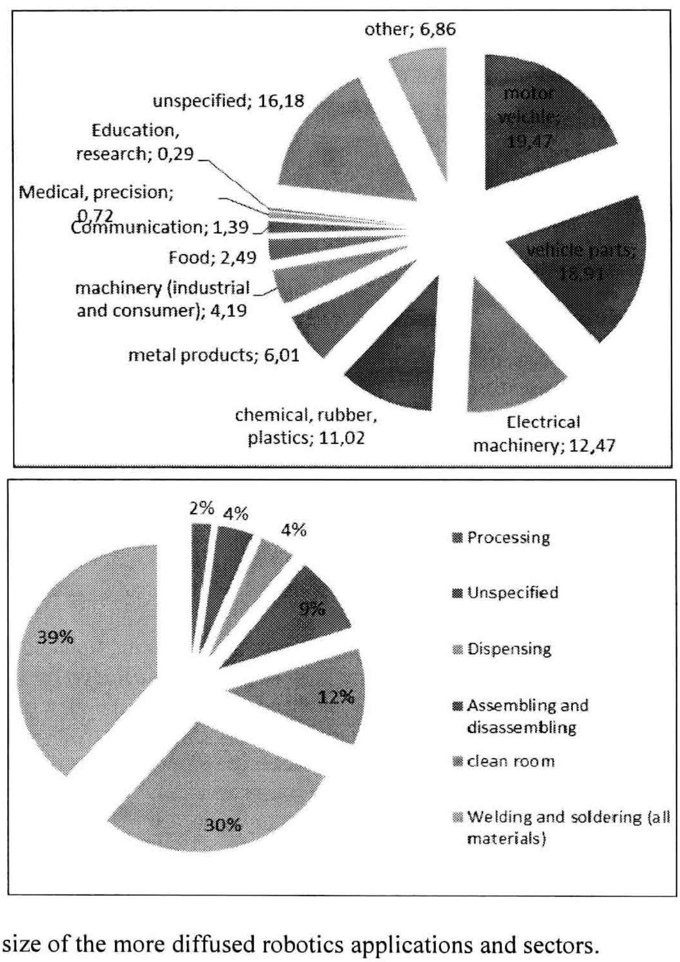


Figure 1. Relative size of the more diffused robotics applications and sectors.

The automotive industry has been the main driver to the use of robots in its production plants introducing their use also along the whole supply chain.

Motivations on the use of robots include mainly the requirement to perform tasks in hazardous environments (e.g. powders, foams, explosive or inflammable environments) or hazardous work-pieces (e.g. high temperatures, toxic materials, heavy loads), the requirement to improve quality and reduce defects and also to increase the production.

Statistics show a positive growing trend for the robotics market till 2008; in 2009, the global economic breakdown led to a significant crisis also in this sector. However, as shown in Figure 2, during 2010 various regions experienced good recovery rates in robot sales. Asia was on top with an increase of 127%, the second highest level ever recorded. About 17,000 units were shipped to Americas, 87% more than in 2009, reaching almost the level of 2008. In Europe, about 30,000 units were sold, 45% more than in 2009. This is however still about 15% lower than the peak levels of 2007 and 2008.

The most dynamic markets, as highlighted by the IFR Statistical Department [1], were China, the Republic of Korea and the ASEAN countries. Sales to these markets almost tripled. In 2010, the Republic of Korea was on top with almost 23,000 robots sold. Japan recovered with a lower growth rate of 66% to about 21,000 units. This is followed by North America which recovered by 90% to about 16,000 units and China with almost 15,000 units sold (+170%). Germany ranked 5th with about 13,400 units sold (+57%). The first quarters of 2011 registered another substantial rise of 18% in robot sales. The electronics industry, the automotive industry and the metal industry were the main drivers of the high increase of robot sales in 2010, as well as in 2011.

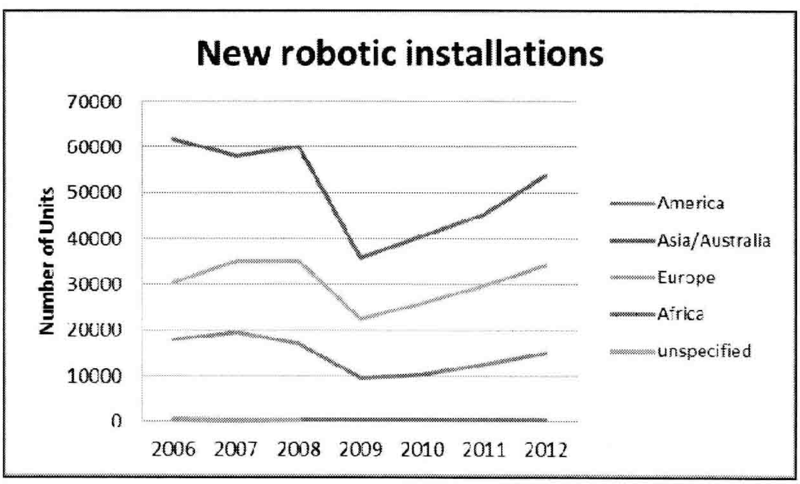


Figure 2. New robotics installations: current trend and forecast.

IFR and EUROP ETP observatory [1, 2] forecast that robot installations will continuously increase also in Europe and in the Americas. The automotive industry is continuing to implement new technologies and materials thus requiring new manufacturing lines. The application of robots in other industries i.e. the food and beverage industry, the pharmaceutical and solar cells industries will further increase. It is estimated that the stock of robots operating in the factories world-wide will increase to about 1.3 million at the end of 2014. Robots will penetrate areas with a still low rate of automation, such as small companies and service companies, due to the improvements in safety, flexibility, accuracy, ease of use of robots and thanks also to the decrease of robot installation costs over labor costs (Figure 3).

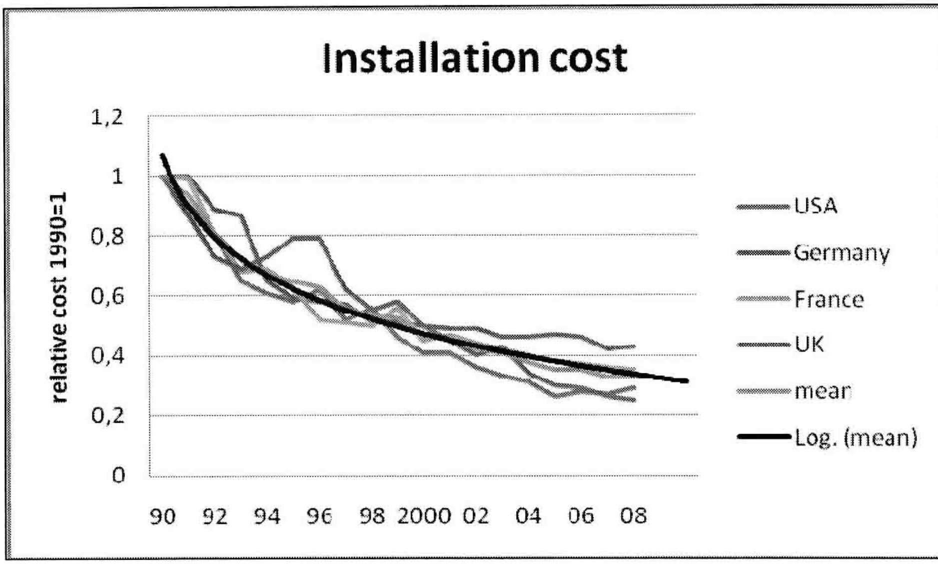


Figure 3. Average robot price with respect to labor compensation.

1.2. Robot Typologies

To better understand how a robot is chosen, the different typologies of commercial robots currently available on the market have to be described. Figure 4 shows the most popular robot geometries. Industrially used robots are classified into four main families:

- a) Cartesian robots (also known as Gantry Robot);
- b) Cylindrical/polar, and SCARA robots;
- c) parallel kinematics manipulators (e.g. "delta" robot);
- d) Anthropomorphic robots.

Each kinematic structure determines a corresponding shape of the working space.

Manipulators of type a), b), and d) are called "serial manipulators" because they are realized connecting in series several links each one actuated by a revolute or a prismatic joint. Each joint is actuated by a motor; the term axis usually denotes a joint and its actuator (linear or revolute motor). The first three joints (main axes) determine the motion of the arm and so the XYZ position of the gripper whose orientation can be modified by 1, 2 or 3 "secondary axes" located in the wrist. Usually industrial manipulators have between 4 and 6 degrees of freedom (DOF). Parallel manipulators are characterized by several links connected in parallel to move the mobile base. Some examples will be described further in this chapter and through the whole book.

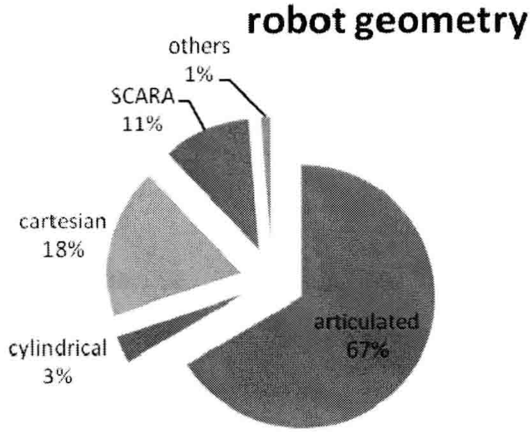
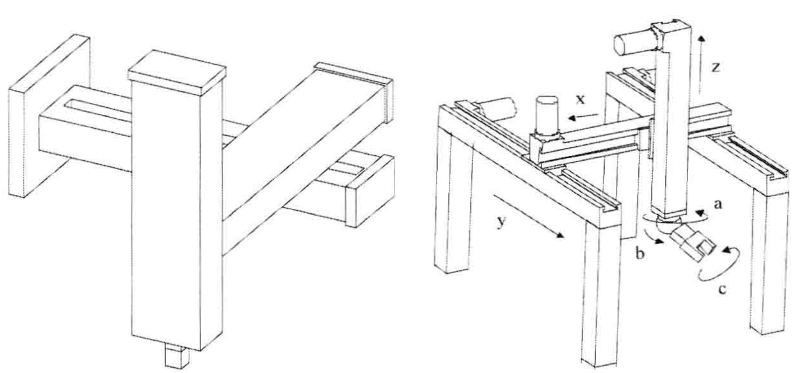


Figure 4. Robot geometries currently on the market.

The name of the manipulator structure depends on the configuration of the three main axes.

Cartesian robots employ linear axes, along X, Y, Z direction. Usually they have additional axes for rotations (wrist with A, B, C rotations). Cartesian manipulators may have the structure of Figure 5; small manipulators are generally of type (a), while the biggest ones have usually a gantry structure type (b). Cartesian manipulators are not commonly used in industrial applications except for machining. They have high machining precision and accuracy due to their intrinsic rigidity. Big Cartesian robots are sometime used to carry and move anthropomorphic manipulators in order to enlarge their working space. The result is a redundant robotic system having the dexterity of an anthropomorphic manipulator with a bigger working space. In this case the anthropomorphic manipulator is generally of a small size with a payload not greater than 30kg. These combinations of manipulators are practically applied to work on large size products like containers or boats. Generally both robots are synchronously controlled by a unique controller. Actually, the controllers of all the major producers of anthropomorphic manipulators are able to control also additional "external axes". Some controllers are able to control up to 36 external axes; however, a number of 9 external axes is common. External axes are also often used to control two or more synchronized working cells.



(a) (b)

Figure 5. Cartesian robot architectures.

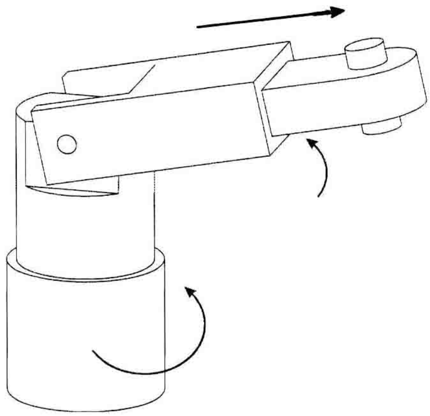


Figure 6. Polar robot.

The term ***polar robot*** properly refers to a robot composed by a series of 2 revolute joints, followed by a prismatic one (Figure 6). Sometimes, in the common industrial practice, also cylindrical robots (Figure 7) are improperly called polar.

The acronym **SCARA** stands for Selective Compliance Assembly Robot Arm. Its basic structure (Figure 8) is constituted by two revolute axes which position the gripper in the XY plane. A further linear axis may be used to impose the Z coordinate. In few cases the Z axis is the first one. An additional axis is sometime employed to rotate the gripper around the Z axis. The two revolute axes incorporate a controlled compliance while the Z axis is rigid. This design allows compensating for inaccuracy in the XY position during *peg in hole* assembly operation, in which small pieces are inserted in bigger ones from the top.

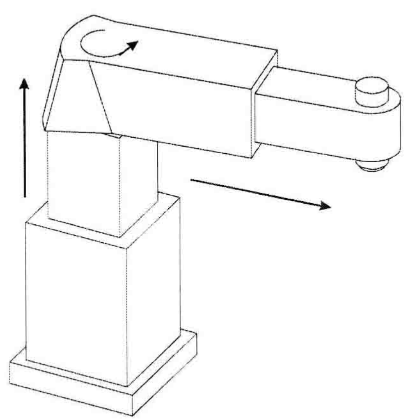


Figure 7. Cylindrical robot.

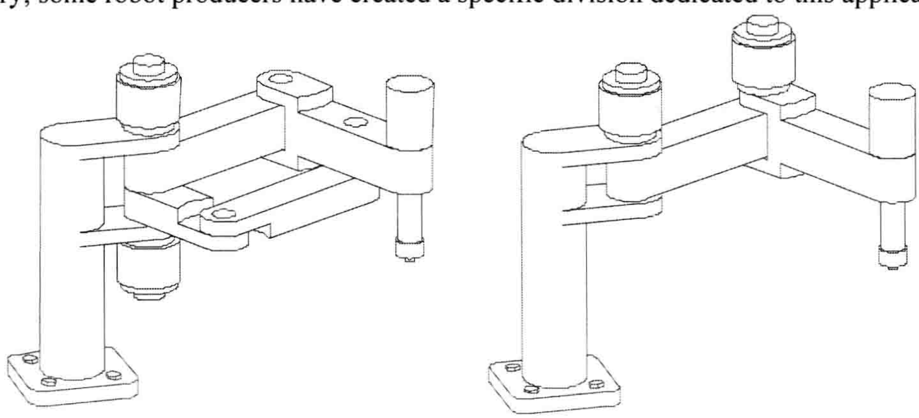
This kind of robot had a big success for its performance (accuracy, speed) and its limited cost. In the recent years it partially lost popularity due to the success of small size anthropomorphic and delta manipulators. However, due to new design trends related to direct drive technology and price reduction, the number of new installed SCARA robots is still significant. However it is useful only for planar applications with limited payloads (20kg maximum); the working space is generally smaller than 2 meters. Classical applications (90% of the cases) are fast Pick and Place.

A particular pick and place working cycle (called SCARA cycle) has been standardized to compare the performance of manipulators of different models and different firms. This cycle includes a return motion composed by three segments: vertical *pick* motion of 25mm, a linear displacement of 300mm and a *place* motion of 25mm. Generally a SCARA robot may perform the cycle in a period between 0.5 and 0.9 seconds depending on the payload. Delta manipulators may perform the same cycle in a shorter time (0.3-0.4 seconds) but with a smaller payload (usually less than 1 kg).

Typical SCARA applications include: fast assembly of electronic products (it is worth to note that many producers of SCARA manipulators are also important electronics producers like Toshiba, Panasonic, Bosch, Mitsubishi), packaging for the Pharmaceutical field or the food industry.

A modification of the SCARA architecture is the cylindrical one. A pure cylindrical structure (1st rotative axis followed by two orthogonal prismatic joints) is seldom utilized in industrial field. On the contrary a combination of rotative and prismatic joints (cylindrical pair) around a vertical direction followed by 2 rotative axes (total 4 axes) is often used for fast and delicate manipulations.

This robot typology is primary used to manipulate silicon wafers in semiconductor industry; some robot producers have created a specific division dedicated to this application.



(a) (b)

Figure 8. Two version of SCARA Robot; a): the actuators of axis 1 and 2 are located on the fixed base, b): the actuator of the second joint is located on the axis motion.

While generally industrial robots have a serial structure, special manipulators may have a parallel kinematic configuration. The most common manipulator having this type of configuration is the DELTA robot (Figure 9). Its structure consists in 3 cranks (parallelograms) which can rotate with respect to the fixed base. The mobile platform has 3 translational degrees of freedom. A fourth leg may be used to transmit a rotary motion about the vertical axis from the base to the end-effector mounted on the mobile platform. The three rotational axes are coplanar and oriented 120° degrees one from the other. At the end of each parallelogram there are two spherical joints. Six rods connect the mobile platform to the cranks by spherical joints. Actuation may be obtained with rotational (DC or AC servo) motors (the most common) or with linear actuators.

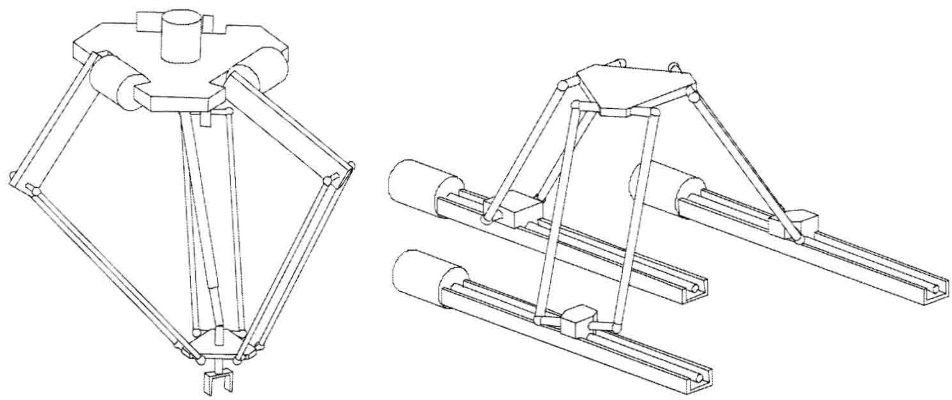


Figure 9. Delta architecture: classical and linear structure (Triaglide).

This manipulator was invented by R. Clavel at EPFL and then patented in the late '80. The license was then bought by ABB Flexible Automation (1999) which sold several thousand manipulators of this type. In 2009 the patent expired and many other companies have developed similar robots with excellent performances. A model by Adept, named "Quattro", obtains the 4th degree of freedom (rotation around z axis) using a 4th crank in parallel to the others.

This type of manipulators is extremely fast, but its payload is quite low. For this reason, they are suitable for high performance pick and place tasks in specific application fields like food industry and pharmaceutics. The payload is between few grams to few kilograms with a cycle time between 0.3 and 0.5 seconds (considering a standard SCARA cycle).

Other types of parallel manipulators (or hybrid parallel-serial manipulators) have been produced (e.g. the Tricept, Figure 10), but no one gained significant diffusion since now. Triaglide (Figure 9 b) is a 3 DOF parallel manipulator able to perform translations in XYZ; the working space may be very large in the direction of the slide joints. Some 6 DOF parallel structures based on the Stewart-Gough architecture (Figure 11) have been proposed for 5 axes machining but their industrial diffusion is very low.

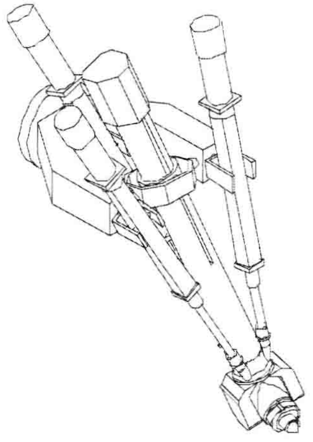


Figure 10. The Tricept architecture.

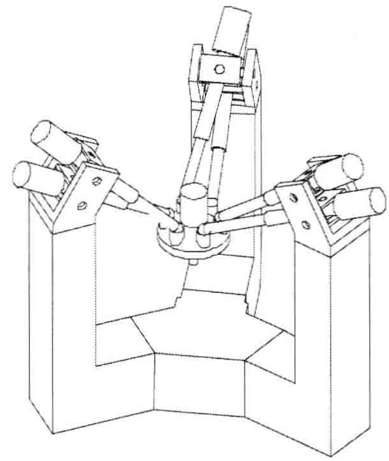


Figure 11. The Stewart-Gough platform.

The Tricept exhibits stiffness and accuracy suitable for machining applications. The 3 dof parallel structure is completed by a 2 dof serial wrist thus allowing 5 axis machining. Its behavior is not isotropic, exhibiting a very high stiffness in one direction. Even if there are some samples implemented on industrial field, the Tricept is still a niche product.

The most diffuse manipulators have anthropomorphic geometry (Figure 11). They generally have 5 or 6 degrees of freedom, thus reaching any point of the working space with the desired orientation of the end-effector. A large variety of dimension, payload and specialization for particular applications is available. The most common varieties of anthropomorphic manipulators are:

- general manipulation robot
- foundry robot
- welding robot (wire welding and spot welding)
- painting robot
- palletizing robot
- clean room robot

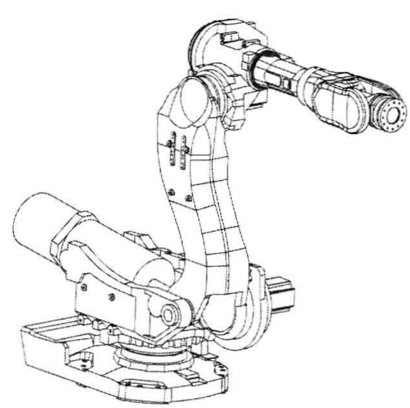


Figure 12. Antropomorphic robot.

Each variety of anthropomorphic manipulators has specific construction details in terms of mechanical structure, actuators, servo-drives and/or controller. Criteria for their selection will be addressed in the next paragraphs.

2. Performances and Criteria for Selection

The choice of the most suitable manipulator for a specific application depends on several requirements:

- application field
- payload
- shape and dimension of the working space
- speed
- repeatability and accuracy

Each of the abovementioned requirements is discussed in the following.

2.1. Application Field

Within a single industrial company many different robotized working cells may be present, each one requiring different robot characteristics. The same type of specific application may be present in different industries. The most common specific processes to be automatized include:

- production of raw or intermediate materials
- treatment and processing of intermediate materials
- welding (spot welding or wire welding)
- assembly
- painting
- packaging and palletizing

Each of the listed application may include quality control. An analysis of the working condition for each application is fundamental to determine the best manipulator geometry useful to automatize the process.

Let us consider a metal die-cast or gravity cast process where a robot feeds the machines and unloads the realized pieces. The robot manipulates cups containing high temperature molten aluminium or steel in a hot, harsh environment. Thus it must have specific characteristics to protect its own mechanical and electrical components. Protections may include special corrosion resistant seals, grease, and even pressurized motors, protection carters, to prevent the penetration of dust, liquids and gasses; sometime total IP67 protection is required.

Sometimes it is sufficient to protect the wrist, but in some circumstances it is necessary to protect the whole manipulator and control unit.