Advanced Mechanics in Robotic System

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ISBN 978-0-85729-587-3 e-ISBN 978-0-85729-588-0
DOI 10.1007/978-0-85729-588-0
Springer London Dordrecht Heidelberg New York

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Cover design: eStudio Calamar, Berlin/Figueres

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

This book provides information of the stage of mechanical design for relevant applications in robotic fields. During recent years, some new technologies have been developed and put into widespread use. Humans have always been fascinated with the concept of artificial life and the construction of machines that look and behave like people. The robotics evolution demands even more development of successful systems with high-performance characteristics for practical and useful applications. For example, humanoid robot is a system elaborated for helping or replacing persons in dangerous or undesirable works. But, it is a complex machine in which an effective design represents a challenge for researchers and scientists. Therefore, mechanical designers have studied suitable methods and procedures in order to obtain feasible results for this kind of biped walking machines. In rehabilitation field, the inclusion of robots is growing up rapidly since the good operation results that have been performed for these automated machines. Mechanical prosthesis of hand, arms or legs have improved the quality of life for handicap people providing them autonomy and versatility. Beside industrial robots, mobile robots can be the most frequent robot devices found in the market; vacuum machines or wheeled and legged robot for inspection or security applications are examples of commercial products that can be bought in a shop or by online. Parallel manipulators have opened a place in simulators market since its high structural stiffness, high payload and high-accuracy positioning in reduced workspace. Airplane simulator, automobile simulators and video game platforms are some examples of practical applications of these kinds of manipulators. The principal drawbacks of parallel manipulator are their limited workspace and losing of stiffness in singular position. The international robotics community has been working for resolving these handicaps by designing novel mechanisms that allow improving the parallel robot operation. Similarly, several innovative solutions for mechanical design of robotic systems have been reported from research centres and universities around the world. The aim of this book is to illustrate originals and ambitious mechanical designs and techniques for developing new robot prototypes with successful operation skills. In particular, humanoid robots, robotics hands, mobile robots, parallel manipulators and human centred robots are our case of study because they represent mechatronic projects with future growing expectation. Since for a good control strategy a good mechanical design is required, a book chapter has been spent on description of suitable design methods thinking of control architecture. I would like to take this opportunity to thank the authors of this book very much for their efforts and the time that they have spent in order to share their accumulated information and understanding of robotic systems.

Madrid, November 2010 Nestor Eduardo Nava Rodríguez

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Humanoid Robots

Luis Maria Cabás Ormaechea

Abstract This chapter is based within the study of the humanoid robots world and focuses specifically on the mechatronic study of them. From a scientific standpoint, will be represented mechanically this anthropomorphic robots (from now, called humanoid robots) as a final link in the evolutionary chain in robotics area. Likewise, the design of humanoid robots is based on a wide range of mechatronic disciplines (such as material science, mechanics, and even biomechanics), and we will try to describe them in this chapter. Therefore, the aim of this chapter is to approach progressively the problem of the humanoid robot design, using physical and mechanics concepts, interacting through analogies with the human body. The chapter begins making a further description of the humanoid robots world, showing the evolutionary process that have undergone this type of robots in recent years. With this run-through of the main important points, we try to describe a general procedure to find a key criteria for successful process design of humanoid robots. This "robot-making" process to explain an analysis with initial theoretical calculations that result in the selection of the various mechanical components of a humanoid robot (actuators, motors until structural components). Then, the objetive of this chapter is to present the comprehensive analysis of mechanical design of a humanoid robot that allows to know and quantify the variables you will encounter along the design process of this type of machines.

1 Introduction

The robotics proposes an attractive point of view of the technology with respect to science. From a purely technological point of view, there are many applications through the use of robots: military and security tasks, health sector, domestic

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N. E. Nava Rodríguez (ed.), *Advanced Mechanics in Robotic Systems*,
DOI: 10.1007/978-0-85729-588-0_1,

services, means of access and exploration of remote or dangerous places, in the industry (cottage, car, heavy, iron and steel) to increase the productivity and the efficiency. Therefore it is expected to generate a wide variety of applications for the robots that will give a technological added to this type of machines, as in any evolutionary technology process. In a scientifical point of view, understand and explain the human intelligence behaviour and then, through this knowledge, try to create intelligent machines still follows one of the greatest scientific challenges and a highly topical subject even, is in this field where could best produce these challenges. On the other hand, one of the best theories related to human intelligence maintain, that the human intelligence can only be understood when it is associated with a physical body (embody) that allows it to interact with the world. So, if we have this kind of gorgeous mechanical machines, it will allow us to advance in modern control theories, so that the robot can not only walk even can run and help in many tasks (dynamically controlled). Finally, the robotics allows research in the design of new sensors and electronic equipment that meets needs in energy savings (to operate in real time) and low cost required for the development of humanoid robots.

2 Robots Coexisting with Human Beings

All of these desires and projects listed above will influence our daily lives. It is estimated that humanoid robots will change it in a large-measure our lives in the future. It is expected from this kind of robots, it will assist people to perform functions in virtually all types of activities. In fact, they are developing robots that assist in housework (cleaning, grass cutting, etc.), security, and entertainment, educational and even robots that assist elderly people or with disabilities. In I + D researches, there are more than a hundred projects related to humanoid robots in the world. The strange thing is that we can draw a parallel of the current state of humanoid robot with personal computers. Just before the discovery of computers (and their high growth rate through the last 30 years), nobody thought that this invention would become in personal computers. Fifteen years ago no one could see the usefulness of phones that they could fit in their pockets. Specifically, humanoid robots offer great technological challenges that once it achieved, it will be most fascinating. Starting with the basic tasks until they have the ability to use the tools that man has been used throughout history and without it has to be adapted to special environments. This may seem easy, but it is very important because it demonstrates the versatility of the humanoid robot in an environment that has been created by opening a wide range of applications (as many work environments).

3 Humanoid Robots: Definition and Classification

Like flying, one of the most sought challenges was to create a man very like him, able to communicate in their own environments and, at some point, be autonomous in its decisions: a robot. In the twenty-first century, the industrial citizen has seen the need to learn in recent years, the meaning of new terms marked by a high technological content. Irrespective of technological advances and the implications of these developments, science-fiction element of our culture will always be a mirror of our concerns, desires, and fears and hope forces for the future. Generally, robots novels and films show a little resemblance the robots that have been manufactured or designed in reality, however, because of their stellar participation in most, if not all, those futuristic movies have allowed us that the term and the machine be more familiar, making easier integrates it into our daily lives before they see the reality. After sometime was enough those we have seen as a real robot, either on a television or print news, and we put aside the myth and we accept the robot as a machine more than our environment, that sort of animated mechanical arm with speed and precision welded vehicle body or insert electronic chips on plates. From there, the rest remained within the limits of our imagination. Robotics as a tool of science fiction (or vice versa), takes its inspiration from reality, from a lack of something or necessity in daily life and exploits it to unimagined future. This revolution not only regarding on definition of robot, but also in its practical applications makes that possibilities for creating will be multiplied.

4 Advantages and Disadvantages

Taking into account the design of this kind of machines, the human had to look into the nature due to its present big part of inspiration for the designers. However the designer concluded that copying exactly the nature is not reliable and it is becoming useless and complex. So scientists of the University of California, Berkley, have focused in one common characteristic in all of the animals that without it, the robot will be useless: locomotion. After numerous studies, one of the most significant discoveries was that, regardless of the number of legs and how to perform the movement, each animal performs the same force to press the soil regardless of the leg in question. Therefore, the principle of motion is the same in all legs. However, bipedal animals have something we do not have as a centipede: greater stability, with respect to the first and greater maneuverability with respect to the second. The advantage of legged locomotion is that each makes the functions as a buffer spring and they all work as a team, led synchronously by the brain in order to do the activity that the animal wants. But paradoxically, if you look at most of the robots that exist today, one can see that they have a common characteristic which is the lack of speed and smoothness of movement. The walk of the robots is very elegant and is a problem that researchers have spent decades trying to solve. However, we will see a more detailed overview of benefits and differences of the walk that the robots actually have:

1. Mobility: Legged robots exhibit greater mobility than those who use wheels because they use intrinsically omnidirectional mobility steering. This means they can change direction on the main axis of the body by moving only their support (legs). Furthermore, they can also rotate about the axis of their body without lifting their legs supported by just their joints, that means that its body can rotate, tilt and change position.
2. Active suspension: Intrinsically, a robot with legs has a suspension for adaptation by varying the height of his body with the position of their legs into uneven ground. In this way the movement can be softer than a wheeled robot because the latter will always be parallel to the ground by adopting similar positions to the relief of the land.
3. Natural ground or Land discontinuous: The wheeled robots require continuous surface in order to move efficiently. At first the robots with legs do not require a continuous ground and may travel along sandy, muddy, steep and smooth land.
4. Landslide: A wheel can slide on a surface because of adhesion, the legs of a robot usually deposit the weight of the robot directly on the ground and the chances of slipping are lower.
5. Average speed: A robot with leg can overcome small obstacles maintaining a constant speed of its body with rectilinear uniform motion if its necessary or if the programmer so wishes.
6. Overcoming obstacles: The robots with leg can overcome obstacles which have low height compared to the size of the robot. On the other hand, a wheeled robot could be stuck if the size of the obstacle is greater than the radius of the wheel.

The tendency in recent years has tried to incorporate robots into daily life within the home or workplace, to do this, it is very important also the design, since they must be able to adapt to different environments which not requiring clear and structured extensive handling, overcome obstacles in height and also makes them look most familiar, always eyeing the Uncanny Valley. Of course, robots with legs are not the general solution of robotic locomotion. They present a series of problems and disadvantages that have kept them out of the use in industrial and service sectors. However, humanoid robots are more complex than those that use wheels with regard to electronics, Control and scroll speed (provided that the surface is flat, of course). But the main disadvantages that we can find are the following:

1. Mechanics: A system for locomotion with legs is much harder to get than those with wheels. The wheel is an extremely simple mechanism. With a single actuator, we can provide motion to the robot, however, one single leg required several kinematic links and joints. One leg needs at least three actuators to allow full movement.

2. Electronics: Each robot joint is associated it with a controller and must be controlled individually. This means that it requires many sensors as joints. A robot with wheels is always in contact with the ground, thus simplifying the electronics.
3. Control: A humanoid must coordinate the positions of all joints to make any move even with very strict guidelines to prevent fall (ZMP Control) and it is certainly more complex than a similar robot with wheels.
4. A wheeled locomotion mechanism on land surface is much faster than a similar mechanism which use legs.

5 Design Methodology

The design process consist of transform information based on conditions, needs and requirements related to the description of a structure, in order to satisfy this structure. Thus, we could say that the person, who designs, is a processor of information. Not only he starts with necessity to get something, but also with knowledge that the designer have acquired, this in order to get this imagined solution become true confirming all the characteristics for those who have been created. Today we speak of design as a science and it recognizes the interaction of a large set of features within its definition, problem solving, decision making, development, learning, knowledge, optimization, organization, satisfaction of needs; all of them are necessary but not sufficient by themselves. In this chapter, in the main topic of this article, we are going to describe the mechatronic design methodology of the natural size of humanoid robot, through a methodology for the design of it, made through the knowledge gained during the design and manufacture of prototypes RH and RH-0-1.

Definition of the Priority Tasks

It is pretended that this developed robot has to look like human beings so that their presence have to be friendly. That means, in general, the prototype. The RH-0 will have a bipedal locomotion in order to move and will have a hinged clip on the ends of their arms to manipulate small objects and a head equipped with sensors, through which the robot could be orient and move in their environment work. Moreover, as one of the tasks of the robot is the attention to disabled people, it has been designed with specific measures for a person sitting in a wheelchair can interact with the humanoid robot (which is a specific constraint objective that we are looking for) but really the applications that can be allocated to a robot of this kind today are many and various, including the following:

1. Human Assistance, for which it must be able to live with people and work well in their environment. Examples of such applications: assistance to elderly or disabled persons, personal assistants in offices, hospitals, schools, hotels and all kinds of public services that can be imagined.
2. Performing physical labor, transportation of goods both individually and collectively with other robots or with humans when it comes to large pieces. In this regard, it is noted the importance of this kind of robots when it comes to transportation in buildings where it is necessary to go up and down stairs, walking through narrow corridors, etc.
3. Periodic maintenance, with this application is intended that the robot perform those maintenance tasks that results dangerous for integrity of the operator, as e.g., electric transport airlines, and inspection of bridges in the reactor core nuclear, etc.
4. Surveillance and rescue work, security and surveillance applications for buildings and people, as well as applications in rescue work in developing natural stress, collapse of buildings, etc.
5. Entertainment and education, the robot must be capable of fulfilling leisure activities such as sports, play. In the case of education, the applications are intended to be guides in museums, explain lessons to students.

With these applications, it is understood that the environments where the robot performs its functions should be unstructured and need to do so in a broad spectrum of possibilities, from an industry to a house, past shops and hospitals, therefore, the robot should be able to walk both flat or sloping surfaces as well as save point, from up and down stairs, up a hill or mountain. Despite the functional diversity that may lead to having this kind of machines, to believe in a multitude of different solutions (in fact, hardly a human being performs the same activity in the same way twice) can be counterproductive to the goal of project, largely because of our imagination. However, we must never cease to be realistic when you assign sizing or assign a PT. This concept of flexibility should be considered as another fundamental requirement to be considered early in the design of the humanoid.

Finally, the basic design of this first prototype, the RH-0, and what we think that will be the “Priority Takes” are the following:

1. Assist human.
2. Walk straight.
3. Walking in circles.
4. Up/down stairs.
5. Incorporate the functionality of human arms when walking.
6. Carry objects weighing up to 750 gr.
7. Gesturing with his arms (pointing, waving).

Conceptual Design

These types of mechanical devices have two major subsystems, divided on kinematic chains defined as lower body and upper body. The lower string is formed by the legs and its primary function is to provide the entire robot locomotion through the environment of action and the upper chain is formed by the arms, hands and head. The union of these two parts form the hip. Like humans beings, the upper is made up by the arms, which can be interpreted well as two robotic manipulators that give you the versatility to help achieve the objective. Furthermore, we find here the torso and back that would be the trunk of the robot whose function due to the lacking mobility, is host of onboard electronics. This part is also responsible for helping maintain the balance of the whole mechanism to shift the center of gravity to the proper position, thanks to the large amount of mass that we have hosted here.

Mechanical Synthesis

Anthropomorphism is a set of beliefs or doctrines which attribute to the divine figure, or qualities of man. One of the most important features of humanoid robots is the spirit in which they are designed. From this point of view it will be taken into account the following basic features:

1. Head: It is very important that all humanoid robots have to need a head in order to present it to the environment. The robot will be devoted primarily to the interaction with the human population. Hence the importance of them look as human as possible, reflected mainly in the face and increased the capacity of gesture that allows the interaction of emotions, in turn, social inclusion. Thus, the face of the robot must be able to reflect the basic emotions (sadness, anger, fear, surprise, happiness and disgust). Besides presenting the face, must possess vision, not for personal use but for their interaction with the user, and for other sensing systems that allow it to be positioned and be oriented in the environment of interaction. For this reason, it is necessary to provide the head of a mechanism in order to be oriented. For this, we should put a DoF whose lines of action coincide at one point and in this way facilitating the kinematics of the same. The head should contain all the necessary mechanisms for all mentioned gestures and are able to work in a future. The use of eyelids, lips and mobile devices that give movement to the brow of the robot will be an aim in the development of humanoid robot. In the future, are also placed here the elements for the humanoid robot to interact through gestures with the human population.
2. Arms: Ideally, we should build an architecture arm 5, 6 and 7 DoF. In most cases, the arms have 5 or 6 DoF, have less than human arms, which is a kinematic chain of 7 DoF. If we assume that the degrees of freedom necessary to position and orient a body in space is 6 DoF human arms would then be

redundant. The advantage provided by 7 DoF is not only the hand is located and oriented, but also the same arm. It is also preferred that the motors are coupled directly to the joints (Direct Drive). This helps to eliminate weight, but mostly mechanical backlash grows over use of broadcasts. This provides the facility to orient and position the arm without changing the hand position, power necessary to avoid obstacles, even find positions that involve less energy expenditure during movement. This should be taken into account to develop the best mechanical system and that will be addressed in this research.
3. Legs: This component of the robot, is the one that will give the necessary support to the entire structure, which involves loading the weight of all engines, machinery, batteries, electronics and various materials involved. On them will swing around the chest and arms balance by looking for correct positioning of the center of gravity. Their engines must respond quickly and in coordination with the whole structure, and also absorb all the momentum that causes the movement.

Study of the Worst Case Analysis (WCA)

Following the analysis of the most unfavorable positions, forget the pair and their subsequent engine, also have been used several hypotheses as demonstrated in his case. From a more practical standpoint, we calculated the most unfavorable positions whether they be more achievable or not. This led, of course, both to very large results as well as those positions impossible to achieve for the humanoid. But the main objective of these states was a first approach to values and also managed, better adapted to the software currently used. Then, based on the theory of ZMP they are opted to take more realistic positions considering ZMP validity and comply with the requirements for each PT.

In conclusion of this stage, we can say

1. In the sagittal plane, we obtained very convincing pairs based on technically feasible positions. Pseudo-state was considered a real for each case.
2. As a prerequisite, you should always consider the ZMP is located within the eligible area.
3. The joints obtained were considerably lower than those estimated in previous analysis because the engine and the structure are subjected at more relaxed position.

Preliminary Design of the Robot

Within these considerations, we point out:

1. Building materials: The materials used in building the robot should be lightweight and highly resistant. Of course the design of mechanical components

should help in this task. On the other hand, one of the major problems in the development of humanoid robots is the energy efficiency because it has not yet developed enough batteries and small electric motors and high capacity, so the optimization mechanical structure is of prime importance.

2. Optimal mechanical design: The performance of the humanoid robot rests essentially on the mechanical design. The pieces should have less inertia possible without sacrificing strength and rigidity. The optimal mechanical design allows to develop lighter and stronger parts, increasing responsiveness. The assembly of mechanical system should produce a stable, solid and robust system. Without doubt, one of the main characteristics that define the robot is that it includes DoF. Talk of DoF is the same as talking about the number and type of movements that the robot can perform. On the other hand, watching the movements of the robot, it is possible to determinate the number of DoF that is presents.
3. Mechanical actuators: We must use effective actuators and strong. However, we are not leaving aside the possibility of investigating other types of actuators, including hydraulic or pneumatic. It is important to develop mechanisms for small actuators that can be housed in very small spaces in the arm and hand. The joints may be powered by mechanical energy conversion devices of an electrical, hydraulic or pneumatic.
4. Balance: For many authors, to achieve a right balance is the most important consideration when designing a mechanical humanoid robot. The primary objective of all design in the biped locomotion is to ensure that when the robot walks it will achieve a dynamic equilibrium. Control methods are used to achieve dynamic balance, however the mechanical design must be chosen so that the robot can respond quickly to the required movements. One method to achieve this goal, is to distribute the dough through the robot in such way that any movement (sudden or not) must to be small. Thus, these movements can be made quickly without generating large moments that usually destabilize the robot. To achieve this, the CoM should be placed as low as possible, to stabilize the inertia of the robot but also fairly high, in order to move only small amounts of mass to correct unwanted behavior. The correct placement for the trunk CoM would be slightly lower, similar to humans. This provides stability and allows the trunk to be moved; changing from place to CoM for accelerations that counter exist unwanted accelerations.

In addition to these considerations, we studied the range of motion of joints in the human being, to keep them as reference in the respective RH-0. So with these concepts we divide the study into two parts:

1. Structure and distribution of the DoF in the arms.
2. Structure and distribution of the DoF in the legs.

So for the arms we required movements that simply are imitating the human walking, extension of the frontal and lateral plane, transport and carry with lightweight things. Based on these concepts, we selected an arm with sagittal mobility and front in the shoulder, sagittal mobility in the elbow and transversal mobility in the wrist; additionally we will place a clamp to manipulate objects. As a summary, 4 DoF in the arm. For the trunk, we recommend one DoF in the transverse plane to enlarge the angle of arm movement around this axis. We prefer this DoF at the top of the column. The result of this study leads us to select the structure of 6 DoF, which guarantees enough mobility for a stable ride similar to human beings. In this type of structure selected, with certain variations, related to mobility in the hip, an area critical to a stable path and in turn keep the stability of the robot, as well as assume the primary role of supporting the upper weight of the robot (torso, arms, batteries, electronic components, etc.). We then have the conventional structure similar to a simple portico, whose bending strength is mainly concentrated in the center of it. This is used by Asimo and most humanoids, due that its good performance has been proved. On the other hand, the novel cantilever structure, that was introduced by the HRP-2, this type of structure allows to distribute the bending stresses in the hip due to higher weight in the robot body.

Calculation of the Mechanical Requirements

The purpose of the dynamics is to establish the relationship between the forces and moments acting on a body, and the movement in which it originates. This relationship in the case of a robot is given by the mentioned dynamic model, which mathematically relates:

1. The location of the robot due to the joint variables defined by its coordinates or for the locations of its end, and their derivatives: velocity and acceleration.
2. The forces and torques applied to the joints.
3. The dimensional parameters of the robot, such as length, mass and inertia of its elements.

To obtain these kind of mechanisms that have a high number of degrees of freedom, the difficulty increases significantly. This makes that this dynamic model could not be done always in a closed manner, i.e., expressed by a set of normal equations of differential type of 2nd order, whose integration allows knowing the movement when applying forces you have to do it for a particular movement. The dynamic model must be solved iteratively using a numerical procedure. The problem of obtaining the dynamic model of a robot is one of the most difficult aspects of robotics, which has been avoided in numerous occasions and that, however, it is essential to achieve the following purposes:

1. Robot motion simulation.
2. Design and evaluation of the mechanical arm.
3. Sizing of the actuators.
4. Design and evaluation of dynamic control of robot.

It is important to know that the full dynamic model of a robot should include not only the dynamics of its elements (bars or links), but also own their transmission systems, actuators and electronic control equipment. These kinds of elements incorporate into the dynamic model new inertia, friction, saturation of electronic equipment, etc. further increasing their complexity. There are two possible approaches to the balance of forces and torques involved on a robot, that result in the so called models:

1. Direct dynamic model: it expresses the temporal evolution of the robot joint coordinates in terms of forces and torques involved.
2. Inverse dynamic model: it expresses the forces and torques involved in terms of the evolution of joint coordinates and their derivatives.

The obtaining of the dynamic model of any mechanism is mainly based on the approach to equilibrium of forces and moments acting on it and respectively established on the second law of Newton and its equivalent for rotational movements, the law of Euler.

Center of Gravity (CoG) Trajectory

Previously justified the desired trajectory for the ZMP, during the progress of the robot along a full step. The kinematic simulations that have been done provides a trajectory considering that all the conditions were not fulfilled, however it was close enough to the desired goal. It shows the evolution of the position of the CoG (blue line) along with the both feet in red on the left, and on the right shows the simulation of robot movement during its time evolution. The main objective, as named above, of all these calculations and algorithms, is the determination of the motors to ensure optimum performance of the biped, at powerful point of view. The selection of these kinds of motors are taken into account the results obtained (with speed and zero acceleration) in quasi-static state. At this stage of the project, it is difficult to find the nature of the mechanical stresses to which they must subject the robot, so it is supposed to a quasi-static state (both their velocities as their accelerations were very low) even though logically the robot moves. Therefore, it is very important for the dynamic analysis of robot, the choice of an acceleration and proper motion velocities, because this selection will depend on torque efforts on its joints and even the possibility of the system to respond adequately with its motors. The way to compensate the quasi-static calculation of stresses generated in the robot to expect a good response and movement of the system, is adding a safety factor to the values obtained (taking into account the inertial factors too), so that all engines are oversized in order to respond to higher loads in an effective way. In addition to calculations, the process of obtaining these permits to establish a set of conclusions is to be taken into account in future designs. Note that carried out an exhaustive dynamic study, can make it difficult and very costly. The dynamic study presented above, has many simplifications and approximations, and yet, its development has been quite complex in the amount of adjustments which have been necessary to integrate the theoretical bases that underpin the analysis and the mechanical structure selected for the robot.

Selection of the Actuators

The aim of all mechanical drive is to move a load at a certain speed and position it where it is necessary. In usual robot actuators they have variable charges depending on the position of the joints and cargo handled at that time. The most widely used actuator system in robotics is the electric-power and represent it approximately 50% of the total weight of the robot. Therefore, the selection process will focus on these kinds of motors (regardless of pneumatic technology, artificial muscles or other). Proper selection of these motors is crucial to get the "best robot possible". The study of the possible variations of the load, its margins and its identification is the biggest effort in the selection process actuator. For the proper selection of actuators, it should make a proper study of the torque that is transmitted for each axis of the joint. To obtain these torques we used the WCA and the inverse dynamic analysis helped by an advanced simulation tools that allow rapid assessment of margins of security to be must put in each axis and allow the robot to reach each position. For example, in the design stage it is needed to locate a new component which is an increase volume (or length or weight) compared to the previous one. It is very useful to know how this change affects the variation of CoG in torque on each axis, to decide where to put it. This process, due to constant interaction with other research groups, although it seems very frequent trivial to perform. Humanoid robots have the characteristic of present low accelerations and speeds and duty cycles of long duration. This is essential in the design of the actuator because it allows important simplifications:

1. Concentrated Mass Model: We will perform static calculations on a model of point masses very simple, based on location of major components and modeled as point masses in certain locations.
2. Worst Case Analysis (WCA): Starting from the proper characterization of the load, identify the worst cases of positions of the robot (of the actuator point of view), in each of the joint axes.
3. Quasi-Static Analysis: The most commonly adopted solution in the selection of an actuator is to use a motor running at high speed with a high ratio gearbox. This is justified by the fact delivering better efficiencies at these speeds and that this high reduction ratio squared divided by a factor of inertia reflected to the motor.

A problem often encountered by the designer is to adapt the engine to the specific load for its optimal operation from a technical standpoint. It is important for this purpose that the engines have the ability to accelerate the load and to move at a preset time without suffering overheating under normal operation. Also to be taken into account is that it shall not cause electromagnetic interference that can affect other equipment or cause discomfort to the user due to the noise produced by its use. In order to optimally design the actuator it is necessary to know well the burden that must be moved by the motor, and this knowledge must be obtained through simulations as realistic as possible of the tasks and the operating environment in which to develop the robot. The selection of an engine has to be accompanied also by the study of power available for this engine. For example, if it has batteries or if it must to design a power system for this kind of actuator. It is therefore necessary to define parallel of all systems on board the robot.

Structural Analysis Behavior

The Process Simulation is an important tool in engineering which is used to represent a process, making this process more simple and understandable. Many times, this kind of simulation are essentials (in other cases not), but without this procedure, the analysis becomes more complicated. The introduction by Computer-Aided Design analysis (CAD) is an essential step in the conceptual design stage. The great development of computational methods (both hardware and software) have enabled us to tackle the resolution of complex analytical mathematical physicists whose decision would be practically impossible. The finite element models (FEM) are used in mechanical engineering for Computer-Aided Engineering Analysis (CAE), a variety of mechanisms or parts, which in turn are fully complementary to the CAD model, which are, basically, geometric representations of these mechanisms or parts. The finite element method (FEM) is one of the most important techniques of simulation and certainly the most widely used in industrial applications and their use is extended to too many physical problems. The FEM method can generate a solid virtual aspect, and from there verify its behavior under different working conditions, study and group behavior, etc. This gives us a more thorough point of view of the final performance of the robot before it is built by detecting problems that would otherwise have been detected or failed after its final construction. The FEM is a very useful and powerful tool that allows a large amount of analysis on components and complex structures, provided by the classical analytical methods.

Mechanical Evolution

The last step in our design process and mechanical design of a humanoid robot, has to do with the process of assembly and final testing.

General Integration

Once the mechanical assembly is finalized, comes the whole integration with electronic components (vision cameras, controllers, batteries, etc.).

Starting Up

Following the launch of the robot and simple testing of communication, various tests are performed to verify the correct operation of each of the subsystems integrated on board.

Laboratory and Outdoor Tests

Both in laboratory and in outdoor tests, work will focus on integrating software control and correct some mechanical problems. It employs a large part of the effort and time in debugging the execution of the movement of walking in a straight line, the more important achievement before getting the other gaits. To get this type of movement with this kind of machine, it is needed to coordinate the actuators of the lower body of robot at all times. Although the reference position at each moment for each axis controllers may be correct, it is necessary to include a correction of the parameters of each controller, depending on the speed of execution of the straight line.

Optimization

Due to changes that occur in the robot, especially in regard to the total weight of itself, it is necessary to redesign and optimization of same. Basically, these changes pointed to two areas of work perfectly distinct but closely interrelated:

1. Redesign based on inverse dynamic analysis.
2. Mechanical changes due to the above point.

Hits

1. Structural Analysis: The robot must strictly comply with the requirements for which will be conceived. Among the tests that will be submitted they should not have structural problems.

2. Design and form of the parts: Each parts are designed starting usually after a study of human beings. Let's say that each piece will respond to its design. If we add, that also will take into account aesthetics; we have a structure pleasing to the eye.
3. Inverse Dynamic Analysis: It is important that the inverse dynamic analysis must be very successful, allowing in a few iterations to solve an issue that could be considered the bottleneck of the design of a humanoid robot. Keep in mind that if you do not have a versatile tool for such calculations the results will affect not only within the scope of related research and in the characteristics of the robot also falling into unnecessary economic costs for the research.
4. Behaviour During a Dynamic Gait: it is true that in mechanics, a good individual performance need not entail a right "group" behavior. However, encompassing the above points, having a correct structural analysis, an effective design and optimized inverse dynamic analysis, the mechanical result can not be other than a global behavior during gait excellent.
5. Robust Platform: the final result is to obtain a stable research platform, versatile and fully adaptable to future improvements.

That is, the possibility to apply new movement patterns, develop new techniques (Priority Tasks), i.e., improve the performances of certain movement patterns with different motor demands in order to contribute to successful participation in different physical activities.

6 Conclusion

With regard to the design process shown and developed in this chapter, we can say that it is very simple and extremely practical, is meeting the requirements at all times and basically taking into account a large number of variables, that when you start a project of this magnitude are unknown. In this chapter we have presented a design methodology applied to humanoid robots with several comments regarding the project RH. The description of these calculations was following the methodology in a more organized way, clear and concise. This methodology has been the result of work by the author, made during the design and construction of the RH-0 and its corresponding development, the RH-1. As a practical application, this methodology rather than proposing a closed instructions to be followed in individual cases, aims to provide some key-concepts for the successful development of a project as complex as designing a technologically advanced machine. It also helps to clarify and provide a starting point to a clear and concise horizon as presented with a large number of variables involved in the design. Like other methodologies, it is presented as the achievement of several consecutive stages but it should be developed in a cyclical and concurrent way. As a general description, we start with the definition of the problem. The main problem remains to reconcile properly the needs of the project (often betrayed by our imagination) with the requirements mechanically possible for a humanoid robot. To do so, has created the concept of Priority Tasks (PT), which tries to cover this problem, where different groups are involved, share the responsibility of trying to narrow in the most realistic way these PT. The proposed solutions must consider and evaluate the possibilities and limitations imposed in addition to the setting where the activity occurs. The result of this phase will be a series of functional specifications and constraints, and the approach of a solution at the conceptual level. However, we must keep in mind that due to the cyclical nature of this methodology should be sufficiently flexible to adapt to continuous changes that may occur later. The second part of the proposed methodology, suggests the development of the solution, by mechanical means of each of the PT previous proposals. This is achieved using the tools provided to us by the mechanics and a constant review and evaluation of the proposed model, that after each iteration, it become more defined, until to be ready for manufacturing. This phase will end with the manufacture and prototype implementation of a positive assessment from all aspects. Finally, the last stage begins after the launch of the prototype and requires the complete functional evaluation of the robot in operation, by testing in different environments and real situations. It is important to highlight the interconnectedness of all the subsystems in the robot, the simplifications that are used to manage the uncertainty associated with the early stages of design and the need for software tools, all connected together under one powerful system information that facilitates the analysis and design decisions with a fundamentally approach holistic. As can be seen, through the application of this methodology, we have found the solution: a humanoid robot.

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Robotic Hands

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Abstract One of the main objectives of the robotic is to make the systems able to interact, modify, transmit and receive information from the human environment. They reach the possibility to replace the human being in simple and basic functions with better results. In this way, robotic hands play a relevant role since they can perform different tasks, such as holding and manipulating, reaching visual communication and obtaining direct contact with the environment, interacting and even modifying it. When we refer to robotic hands the first thing that comes up to our mind is a robotic system that tries to imitate, in the closest way, the skills and shapes that human hands have. There are many different robotic hands and each of them marks a determined improvement in a specific aspect, due to new technology used in its development, since it has been designed from an innovative mechanic system or mechanism. Technology and mechanics applied to robotics help in improving faster. These two concepts, as it is going to be detailed in this Chapter, must be closely related because the efficient use of one of them depends on the improvement of the other. Basing in our classification, it is possible to divide robotic hands in to two types: the multi-actuated robotic hands, directed by technology and helped by special mechanisms, and the underactuated robotic hands, focused on complex and innovative mechanic systems. The second classification adds a new system concept that allows generating several and independent tasks fulfilled with only one actuator, referring to a new generation of robotic hands able to manipulate in a more dextrous way. In this Chapter, robotic hands will be analysed from its technological and mechanical aspects. First, there will be a brief explanation of robotic hands that have incorporated innovative mechanisms or new technology. Afterwards, the Chapter will focus on functional problems that can be found in the robotic hands development. Finally, some

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N. E. Nava Rodríguez (ed.), *Advanced Mechanics in Robotic Systems*,
DOI: 10.1007/978-0-85729-588-0_2,

solutions will be detailed through mechanical systems and how they can affect the development of new robotic hands, studying the case of underactuated architectures.

1 State of Art

The robotic hand of the Robonaut, the humanoid robot for space applications, developed by the NASA (Ambrose et al. 2000; Bluethmann et al. 2003) is probably by this time the robotic hand that is the more similar to the human hand. The Robonaut has been designed to help the astronauts in their space tasks (Extra Vehicular Activity(EVA)). It has been reached after many years of investigations driven in exclusivity to humanoids. Its first predecessor was built in 1973, at the Johnson Space Centre (NASA). This mobile robot was formed by two arms with non-anthropomorphic hands in its extremes, and stereo cameras to reach a tri-dimensional vision. The Robonaut is endowed by a technology superior to its predecessor's, which refers not only to its electronic but also to the level of its materials, actuators and intelligent control system. The objective of the Robonaut is to replace the astronauts in their ship tasks not only inside it but also at the outside and in places where the human being might be in danger. For that reason the robot was conceived with similar shape and size to the human being and is tele-operated. It can also manipulate and hold astronauts tools, and scroll for similar environments. The Robonaut has only one leg with one anchor at its end that allows it to fix to prepared surfaces. Apart from being the first humanoid robot to have slight movement and a torque-force control to make them, the dexterity of its hand named the Robonaut Hand is sufficiently elevated as to fulfil tasks which were almost impossible to reach by the rest of the robot hands of the same era. To make this possible, the weight and size of the Robonaut Hand are absolutely anthropomorphic (Lovchik and Diftler 1999). It is able to make similar movements and to have a similar dexterity to the human being. Four fingers and one thumb, together with a wrist and a forearm, form the Robonaut Hand. It has 22 degrees of freedom or joints (20 at the hand and 2 at the wrist), from which 14 (12 of the hand and 2 from the wrist) are remotely controlled and driven by brushless motors located on the forearm. The cinematic of the equipment is close to the human structure, in a high proportion. The hand is clearly divided in two parts: the Group of elements that are part of the manipulation with dexterity, and the Group which participate in the holding and that allows the hand to maintain stable an object. With this structure the Hand fulfils the principal characteristics required to manipulate general-purpose tools in activities inside the EVA, as mentioned in several articles (Jau 1994; Jau 1995). The dexterity group is formed by two fingers with three degrees of freedom (index and middle) and a thumb, while the holding Group is formed by two fingers with one degree of freedom (ring and little fingers) and the palm of the hand with its degree of freedom. As another example we can mention the Ultra light Anthropomorphic Hand, developed by the Karlsruhe

Research Centre. It is one of the lightest robotic hands, which exist considering the relation size-weight. Its main objective is to be the start of a new investigation area dedicated to robotic hands developed humanoid robots or as human prosthesis. The structure of this hand is formed by 17 independent elements and 18 joints of which 13 (three on the wrist and ten on the fingers) are controlled. The size of the Ultra light Anthropomorphic Hand is higher than the human being's (Schultz et al. 2001), but it maintains its anthropomorphic cinematic. This can be understood to be a first testing prototype design. This robotic hand is divided in three sections. The first formed by the fingers, which have actuators, flexion sensors and touch sensors. The second with a metacarpus that has space enough to host the micro-controller, the micro-valves, the energy source and a micro-compressor. The wrist that hosts the necessary actuators to flex the hand forms the last section.

One of the technological improvements that this robotic hand offers is the development of flexible hydraulic actuators, which have a positive size-strength relation. These actuators, due to its special design, are fully integrated inside the fingers and make complex movements even though their manufacturing cost is considerably low. The structure of this actuator is basically formed by two elements that join the mobile parts and, also, act as a hinge. Inside it, there is located the flexible hydraulic actuator that divides the two elements, making the movements and providing the necessary strength when fluid is injected. The advantages of the pneumatic actuators are: robust construction, ability to make large forces (from the 3 N until the 6 N, depending on the joints) and a high efficiency (Schultz et al. 1999). GIFU has been developing robotic hands since 1997. During that year the first robotic hand, the GIFU Hand I, was made public (Kawasaki and Komatsu 1998; Kawasaki and Komatsu 1999). The GIFU Hand II (Kawasaky et al. 2002) was known in 1999; the GIFU Hand III (Mouri et al. 2002) during 2002, and the last one, the KH Hand Type S (Mouri et al. 2005), in 2004. These four robotic hands look similar due to the fact that the design concept was remained in all of them, modifying and improving certain aspects related to technology and material during each development. These hands were designed as a research platform in holding and manipulating areas. For that reason, they are compact, light and anthropomorphic, in what refers to its size and shape. Another important aspect that remained in the evolution of the GIFU robotic hands is their easy maintenance and manufacturing. The GIFU Hand III's thumb has four joints with four degrees of freedom. However each finger has only three degrees of freedom, giving a total of 20 degrees of freedom to the hand from which 16 are controlled. They also have four joints with an orthogonal axis near the palm that simulates the movements of a human hand. This structural configuration, along with the sensors used (FSR sensors with 859 contact points), helps the GIFU Hand II to have a large ability to manipulate objects, simulating the human hand in an effective way. In what integration refers, the robotic hand can be mounted in any arm because its functioning is absolutely autonomous. Also Bologna University is developing robotic hands since 1988 when they presented their first prototype: the UB Hand I (Bologni et al. 1988). Its second version, the UB Hand II was manufactured in 1992 (Bonivento et al. 1991; Melchiorri and Vassura 1992; Eusebi et al. 1994).

The third and newest version, the UB Hand III (Biagiotti et al. 2003a, b; Biagiotti et al. 2004; Lotti et al. 2004; Lotti et al. 2005). The structure of the UB Hand III is totally different from the previously mentioned robotic hands. It adds new technology and new design concepts. It is formed by one palm, one thumb and four fingers. All the fingers and the thumb have four degrees of freedom and have the possibility to be actuated independently or in pairs, like the human hands. The structure of the finger is particularly different from traditional robotic hands. Its design is inspired in the biological model of the human hand. It has no conventional rotate joints. On the contrary its phalanges are coupled by elastic hinges auctioned by tendons. This design concept makes the finger to be more simple and economic, without damaging its functionality (Lotti and Vassura 2002). Finally, the finger is covered and protected by an elastic and synthetic material that imitates the texture of the human skin.

In regards to the kind of actuators used, they are now considering two alternatives: actuators based on McKibben's Artificial Muscles, or brushless ball screws engines. In any case, designers assure that this robotic hand has the versatility to adapt itself to any kind of actuator, considering not only the existing ones but also those, which can appear in the future. Due to the little free space that remains on the robotic hand structure, the total of the actuators are located on the forearm. Shadow Robot Company is a robotic company that has focused, during these last years, one of their principal research areas to the development of a human hand, named the Shadow Hand. This robotic hand has had many prototypes with different versions of each. They have improved since then Prototype A until the latest named Prototype C. Basically the difference between them falls on technological advantages in control material, new material, structural improvements and more advanced configurations which imitates better the movement and cinematic of a human hand. The Shadow Hand is a robotic hand integrated to its forearm, where all the actuators are located. For that reason it cannot be used separately (Walker 2003; Reichel and Company 2004; Rothling et al. 2007; Shadow 2007). Materials used for the construction of the structure of the prototype are a large variety of synthetics, aluminium, steels and other specific materials, making the hand to weight 3–9 kilograms (without considering its pneumatic energy source) in its last version. The structure of the Prototype C is formed by 25 joints or degrees of freedom, which are all controlled. This allows the hand to fulfil tasks similar to the ones done by a human hand. The robotic hand is driven by the pneumatic actuators based on the McKibben's Artificial Muscles. Its movement is guided from the forearm until each joint through the tendons. For the correct functioning of the robotic hand 40 of these actuators are needed. The control system and the electronic of the prototypes are what have been mostly improved. They started with slow, voluminous and cost full systems. By now, it is all integrated in the same robotic hand, which means an advantage for its use in different environments outside laboratories. The Deutsch Aerospace Research Centre (DLR) begun by middle 90 s a new phase of the design of robotic hands, which named DLR Hands. This investigation area had the main objective of developing a manipulating arm, of which exists three prototypes: the LWR-I, the LWR-II and the LWR-III, which is not only the latest and more advanced but also the one tele-operated from the inside of the ship or from central control, for space purposes and tasks (Hirzinger et al. 1994). Based on the first prototype DLR Three Finger Robotic Hand (Liu et al. 1995), two other robotic hands were built: the DLR Hand I and the newest and more advanced DLR Hand II. The DLR Hand I was designed in 1997. It has a palm, three fingers and a thumb formed by 17 structural elements with a total of 16 degrees of freedom. 12 of them are controlled. The three fingers and the thumb are equal. The difference of this Project was to have all the actuators integrated on the palm or directly on the finger joints. The structure of the hand is formed by almost 1000 mechanical components. The DLR Hand II adds an improvement in areas such us actuators, materials, sensors, control architecture. Strategically, important efforts were done referring to the holding technology (Butterfass et al. 2001). The configuration of the robotic hand keeps its semi- anthropomorphic structure: one palm, three fingers and a thumb formed by 18 structural elements. They have 17 degrees of freedom from which 13 are controlled by actuators (electrical engines). The DLR Hand II adds an open skeletal structure with an easier maintenance and a reduction in its built costs. The palm has the possibility of being reconfigured depending on the object it is asked to hold or manipulate. The thumb and the fourth finger can change its position helping the palm in its tasks (Borst et al. 2003; Butterfass et al. 2004). Even though the philosophy of locating all the actuators on the palm and on the joints remains, the actuators mounted are stronger than the previously used in its predecessor. They have the ability of reaching strength of 30 N on the fingertips. On the other hand, the actuators movement is transferred to the joints through the Harmonic drives and the reducing which enlarge their precision. In what material refers, the fingertips were covered by silicone. This means a progress on the object subjection approaching the Project functioning to a human hand. In what robotic clamps refer, we can mention the Barret Hand, developed by the Barrett Technology Inc. Company in 1988. It was one of the first non-anthropomorphic robotic hands with a complex control system that was commercialized. It has been evolved through the years keeping its configuration. However, what have changed are the building materials, actuators sensors and control systems (Townsend 2000; Barrett 2008). Since its creation until today a large number of universities, technological institutes and innovating companies use the Barrett Hand as a platform for their own developments and research, as it is recognised as a versatile and robust robotic clamp. It has one palm and three similar fingers. Two of them are able to change their position to get even parallel and on the same direction of the third finger. Each finger has two joints auctioned by only one electrical engine. On the palm there is a fourth engine in charge of locating the two mobile fingers. These actuators reach strength of 15 newton on the fingertips. The total weight of the clamp is of approximately 1.18 kg. A newer robotic clamp is the High-Speed Tokyo Hand. The High-Speed Tokyo Hand is a hand specially developed to get object at high velocity (Namiki et al. 2003). The design philosophy used in this robotic clamp is based on maximizing the strength it can reach and minimizing the number of mechanisms used. It is focused on three aspects: low weight, high velocity and acceleration, and finally the precision. The structure of the High-Speed Tokyo Hand is formed by three fingers mounted on a platform that cannot be considered a palm named right finger, index finger and left finger. The index finger has two degrees of freedom while the right and left fingers have three degrees of freedom each, reaching a total of eight degrees. Each joint is driven by a mini-actuator of high performance with Harmonic Drive reducers, specially designed and suited for them. For the censoring, they have located in each joint some strain gauges and a vision system. The mechanical set of the hand weights only 800 g.

2 Multi-Stage Robotoic Hand Design Philosophy

It can be said that the design philosophy of robotic hands are nowadays divided in three groups: multi-actuator robotic hands, underactuated robotics hands and the robotic clamps or grippers. The difference between them lies in the number of actuators they have and the degrees of freedom they are able to control with those actuators. Considering the level of the manipulating or holding tasks able to be reached by them, a scheme comparing them with the human hand is shown in Fig. 1. As it can be seen, if the number of actuators or the degrees of freedom affects the design philosophy, we realise that even the underactuated robotic hands and the grippers have a certain relation, there is an important space between these two groups and the multi-actuator robotics hands. Figure 2 represents a scheme of the design philosophy based on actuators and focused on the multi-actuator robotics hands, and in Fig. 3 appears the same scheme but focused on the underactuated robotics hands and on the grippers. What the Multi-state Robotics Hands design philosophy proposes is to define them in regard to the states they can offer to their driving system, considering as driving system their actuator or group of actuators that offer the movement to the degrees of freedom of the robotic system.

On the other hand, each driving system has a unique driving degree that makes it suitable for a specific robotic system or robotic hand, in this particular case. As a conventional actuator can offer only three states as a maximum (two movements plus a static or standby states), it can be said that the driving degree of a system is 3^n, where n is the number of actuators of that robotic system. Mathematically, the driving degree of a driving system can be represented as:

$$\vartheta = x^n, \tag{1}$$

where x is the number of states offered by a determined actuator and n is the number of actuators a driving system has. If Eq. 1 is generalized for a driving system that might have many actuators and from different kind, the value of θ would be of:

$$\vartheta = x_1^{n_1} \cdot x_2^{n_2} \cdot \ldots \cdot x_m^{n_m} \tag{2}$$

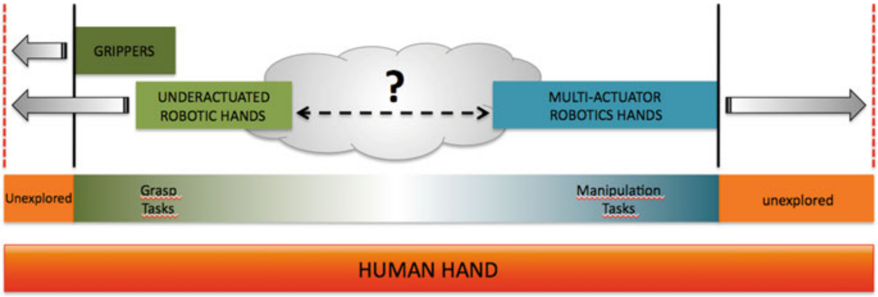


Fig. 1 Differences between multi-actuator hands, underactuated robotics hands, grippers and the human hand

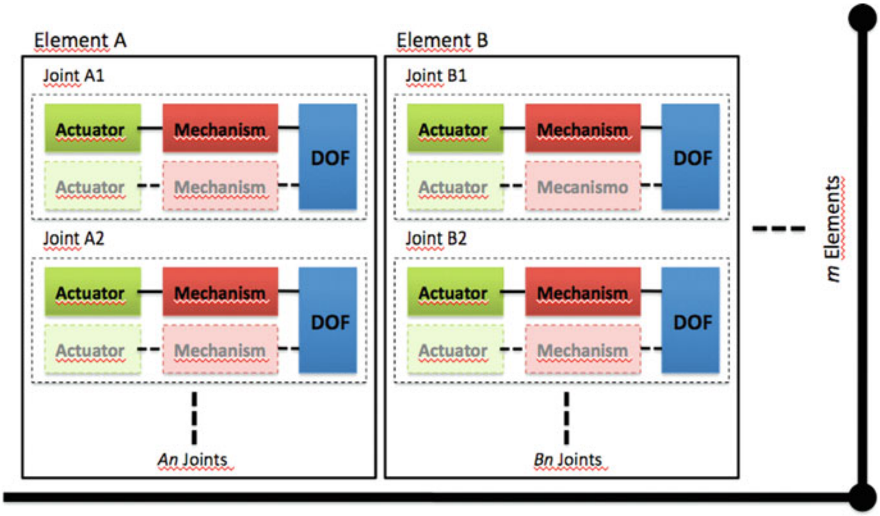


Fig. 2 Actuator based philosophy focused on multi-actuator robotics hands

$$\vartheta = \prod_{j=1}^{m} x_j^{n_j} \tag{3}$$

The elevated driving degree of a robotic system does not assure high skills or high functionality due to the fact that these characteristics are also associated to the structural configuration, the sensorial system and the control system of a robotic system. However, it can help to give an idea of the ability a driving system can give to reach complex tasks. A low driving degree in a robotic system means a high limit for complex tasks. This concept sums up the limits robotic clamps and underactuated robotic hands have in order to do complex tasks in regard to its

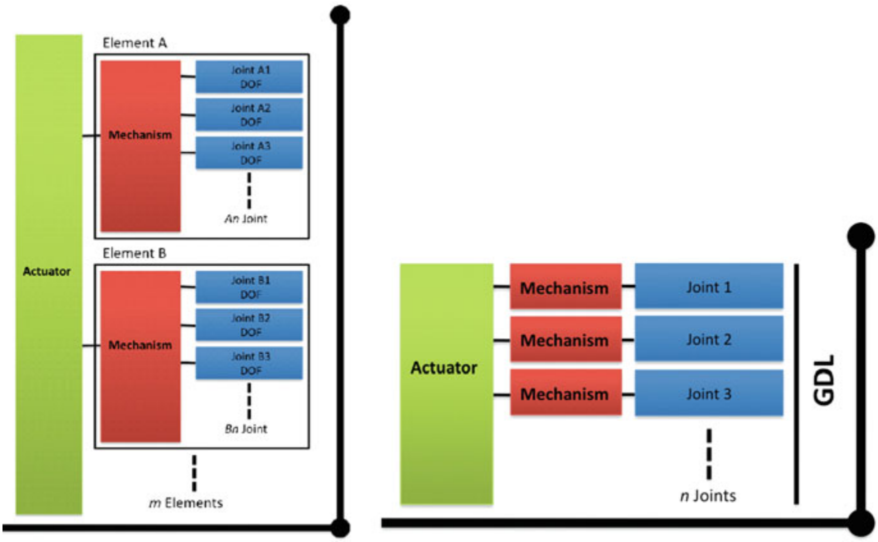


Fig. 3 Actuator based philosophy focused on underactuated robotics hands and grippers

driving degree. Consequently we can say: "to enlarge the dexterity degree of a robotic hand is fundamental to increase the driving degree of the system and this can be only reached in two ways: arising the number of actuators (n) or increasing the number of states each actuator can offer (x)". This can be illustrated in the following way: three actuators offer three states each; they have the same driving degree than a unique actuator able to offer 27 states, because:

if $x = 3$ and $n = 3$ we have:

$$\theta_1 = 3^3 = 27 \tag{4}$$

and if $x = 27$ and $n = 1$

$$\theta_2 = 27^1 = 27 \tag{5}$$

Consequently $\theta_1 = \theta_2$, the two driving systems are equivalents and have the same ability to approach the same tasks even if one of them have only one actuator. With this new defined concept, it is possible to join the simplicity of the robotic systems with a minimum number of actuators (underactuated robotic hands and grippers) with the complexity of those, which have a large number of them (multi-actuated robotics hands). It is possible to approach the large number of states to make different tasks using the control of only one actuator, replacing the dexterous that could be reached by a group of independent actuators. This new design philosophy focused more on the states of a driving system than in the number of actuators it may have, is named "Multi-States Robotics Hands" and can be seen detailed on the diagram of Fig. 4. To make this philosophy acceptable is

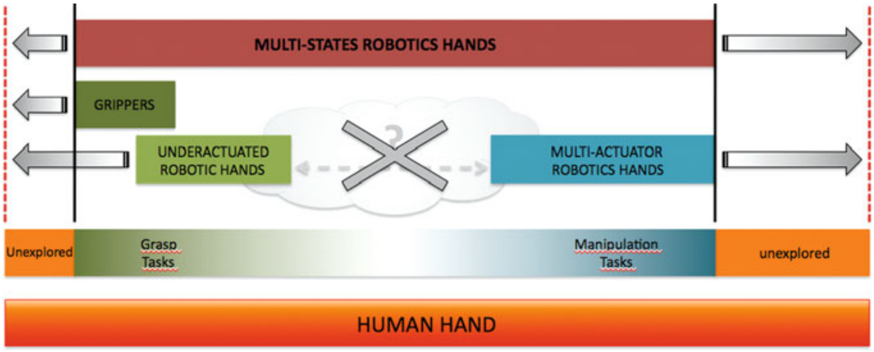


Fig. 4 Multi-States Robotics Hands

necessary to find an actuator able to offer inside a driving system independent states at different degrees of freedom in a robotic system. This means that a Multi-State actuator should be developed in accordance to Fig. 5. Three different states can be defined in a driving system: static states, discrete and relative, all of them depend on the involvement or effects caused on the robotic system.

1. Static states: A state that does not act on the robotic system, making the element of the robotic system on which they act to remain unalterable in time.
2. They act over the robotic system. This state can take two different movement ways but its absolute value keep constant in time for a certain action.
3. Relative states: They act over the robotic system. This state can take two different movement ways but its absolute value can vary in time for a certain action.

On the other hand, an actuator can offer a discrete state when, once approached its action, it is not possible to have a variation on its velocity associated parameters; and every time that actuator fulfils an action, the movement is the same. This characteristic can be seen in industrial pneumatic clamps and also in electrical engines that are in lack of any kind of velocity control. It can be affirmed that all the states offered by actuators nowadays are relative states. This is due to the fact that, in order to guarantee the real control of determined tasks at all levels, it is fundamental that the states offered by a driving system are relatives which means that they should be able to vary the actions characteristics in any time or, what is almost the same, to have the possibility of being controlled to give a determined consequence to each action inside the robotic system. These kind of properties are the ones that make the humanoids walk at different velocities, the robotic arms to reach specific paths and the robotic hands to manipulate objects with different configurations. For that reason, it can be said that the driving system to be implemented on a robotic system should offer only static and relative states leaving the discrete states for specific actions that need no determined control.

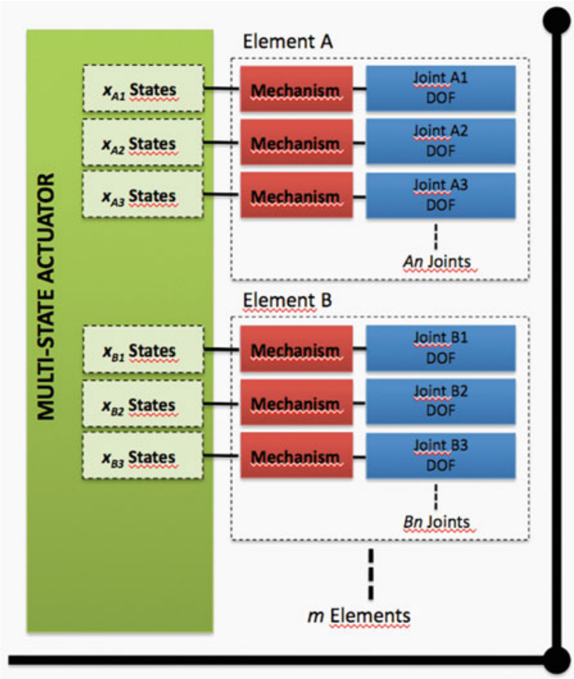


Fig. 5 Actuator based philosophy focused on multi-states robotics hands

3 RL1 and RL2 Hand

The first robotic hand designed under Multi-State Robotics Hands philosophy was the RL1 Hand. It was developed by the Robotics Lab of the Carlos III University. The second generation of the RL1 Hand, the RL2 Hand, has two important aspects that differs it from the first one: the improvement of its mechanism and the finger configuration dedicated to reach more functionality without modifying the initial concept. Both robotic hands have been designed to be mounted on the robotic arm MATS, even though it can be mounted in other robotic systems with only minimum changes thanks to its configuration. The MATS (Fig. 6) (Balaguer et al. 2003; Giménez and Balaguer 2003; Giménez et al. 2004, Correal et al. 2005, 2006; Balaguer et al. 2005) have also been developed at the Robotics Lab of the Carlos III University and it emerges as a concrete use of the auto-contened and symmetric robotic arm that has also been developed for the experience and knowledge of the same group of people. The objective of the MATS robot is to add a tool of high technology for daily use of disabled people, elderly people and people with special necessities at home and other quotidian environments. It was meant to be mounted on the wheelchair of the user and to also scroll through prepared environments in which the user unfolds such as their own house or workplace. To make it possible, the MATS was conceived as an arm with five symmetric degrees of freedom that allows it to perform all the tasks with the same functionality, regardless the extremity from which it is held. The RL Hands

Fig. 6 Robotic Arm MATS—Robotics Lab of Carlos III University

specifications have been restrictive due to the fact that they were supposed to be hosted inside each docking and were also supposed to leave the arm when necessary.

RL1 Hand

Even though there have been many formalities that have narrowed the freedom of the design of this robotic system, they have also caused the rethink of several design parameters of the actual philosophies. It also forced a more exhaustive analysis and at a lower level of the robotic system, the driving system and how to give it more functionality, in this case, to the robotic hand. As it has been previously mentioned, by the time the RL1 (Cabás and Balaguer 2005) was designed, the MATS were already developed and were causing its initial experimental results. That is the moment when emerges the possibility to design a new robotic hand to be perfectly able to be integrated to the arm and to have more functionality. However it was required to be created under several parameters already established by the development. Those parameters were:

1. Integration: The integration of the RL1 was supposed to be complete. This implied the RL1 to be created inside the arm but not damaging the functionality of it.
2. Weight: The new design should diminish the inertia moment to the extreme of the arm and to improve the end load. The weight saved at the RL1 should be won in loading.
3. Size: The size of the RL1 was restricted to the interior dimension of the anchor.
4. Functionality: It was required to hold daily objects by an ordinary user in their personal environments and workplaces.

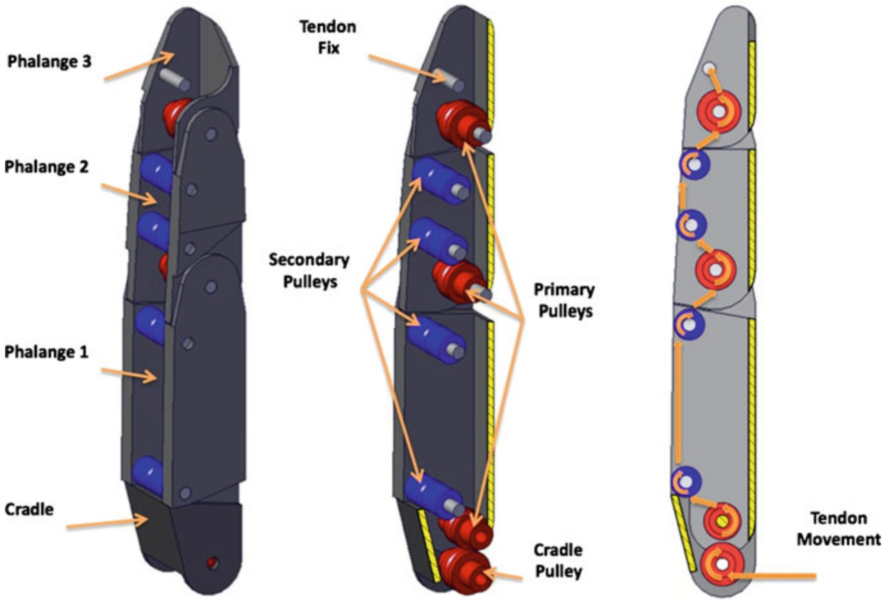


Fig. 7 RL1 Hand's finger configuration

5. Driving system: The driving system, as the control system, should be hosted inside the anchor, indirectly restricting the design in strength and number of actuators it should have.

Once these pre-established requirements were defined, the general configuration of the RL1 Hand were detailed as:

- Number of fingers
- Palm configuration
- Number of DOF and actuated DOF
- Kind of actuator
- Kind of Strength Transmission
- Involved mechanisms

Finally it was concluded that the RL1 Hand should be formed by one thumb with two degrees of freedom plus two fingers opposite to it, with three degrees of freedom each. They would be fixed over a plane and static palm. Apart from the palm, all the RL1 Hand structure should enter and leave the MATS anchor when needed by the user. The final design of the RL1 Hand was divided in two subsystems: the finger design and the driving system design. The driving of all the joints of each finger is done by tendons and poleis, and driven by a main pulley that is part of the driving system. In Fig. 7 is shown the location of the primary and secondary pulleys that make the pair to each finger phalange and also the tendon trajectories through it.

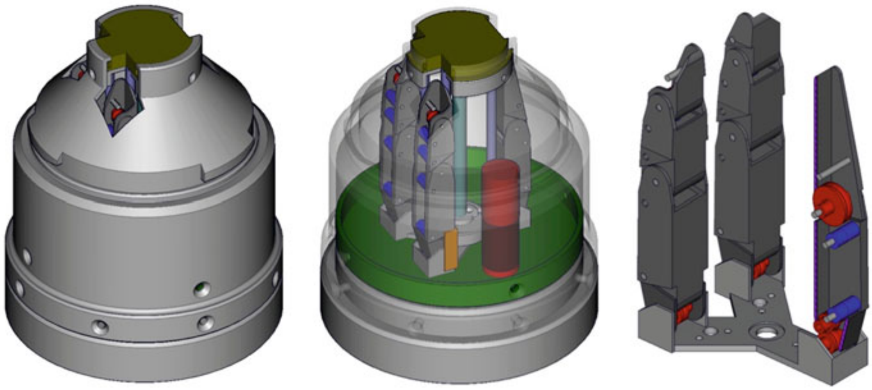


Fig. 8 Location of the RL1 Hand inside the docking

Most of the robotic hands that exist nowadays are mounted on the extremities of a robotic arm. It is said that they are available at any time as it is only necessary to move the hand to the necessary place to approach the tasks. They are in an operative state without the need of a previous movement through an actuator system. For the RL1 Hand, this situation is different as it is situated inside an anchor (Fig. 8).

It requires not only moving the hand to the necessary location but also a previous step to put the hand in an operative state. For that reason, the RL1 Hand should pass through an intermediate step that allows it to leave the anchor in order to be operative afterwards. The actuator system should provide all the necessary states the RL1 Hand might need to achieve holding tasks and, apart from that, should develop all the movements to pass from the different states: standby to operative. A specific design for the RL1 Hand of an actuator system is shown in Fig. 9.

The driving system of the RL1 Hand is formed by an energy transformer that provides three states to the two mechanisms named MA1 and MA2. Both mechanisms give movement to all the robotic system elements. Only one of them works at a time, thanks to a specific mechanism.

This allows the energy transformer to send its movement selectively to each Max depending on the state of the Hand. The extraction system is shown in Fig. 10. In it is possible to see, apart from all the elements that form it, a mobile platform named Main Platform, which moves in only one direction through the Guiding Columns. The central Main Axis that transmits the movement of the energy transformer and the state selector mechanism, which is solidary to the Main Platform, makes this Platform to move up and down positioning the fingers outside and inside the anchor. The states selector mechanism, thanks to a mechanical fusible hosted inside it, passes from a spindle which runs over a central Slotted Axis to a pulley that hosts the tendons of the three fingers and transmits the moment generated by the energy transformer to each joint, every time the main

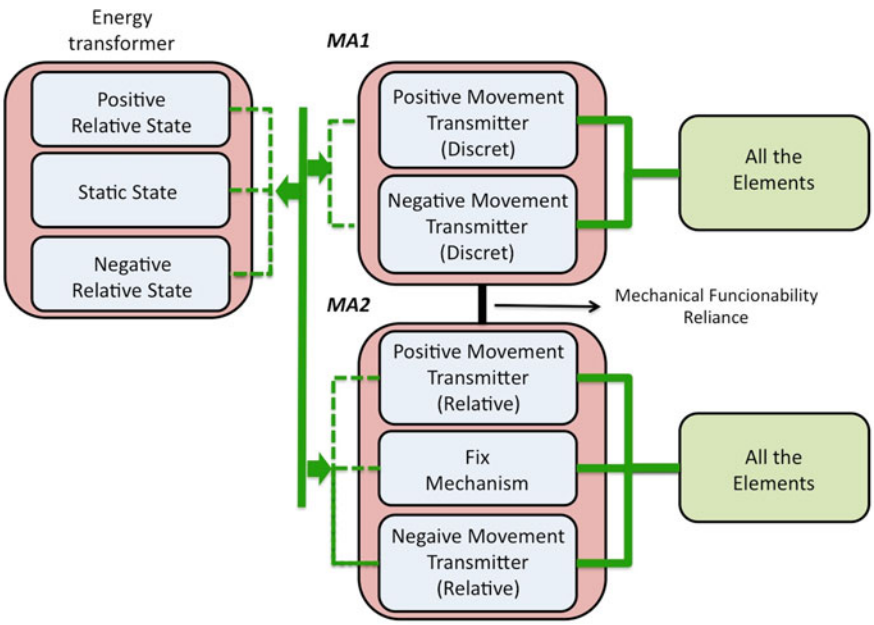


Fig. 9 RL1 Hand's driving system

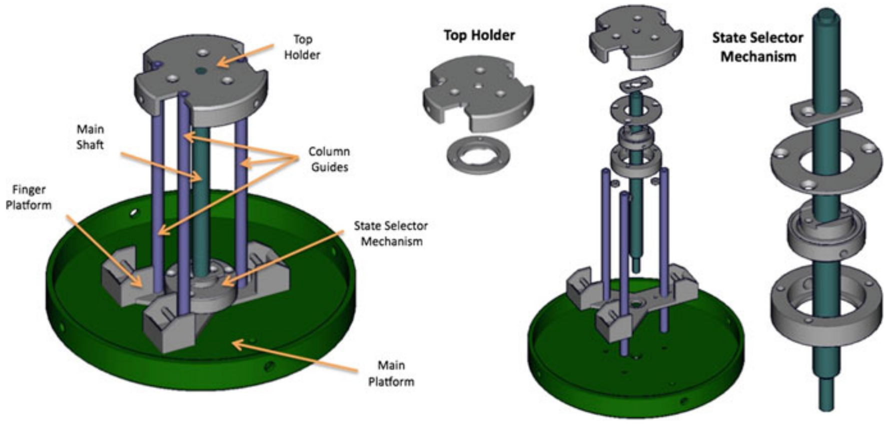


Fig. 10 Drive system integrated inside the RL1 Hand's structure

platform finds a limit at the Top Bracket. The fingers and the thumb are hosted in a cradle. The main function of these cradles is to allow the fingers to remain in a parallel and straight position inside the anchor. As it is seen in Fig. 7, the cradle pulley helps the tendon to pass in an inverted way. For that reason, the joint that corresponds to the cradle rotates in a contrary way to the rest of the joints. Another

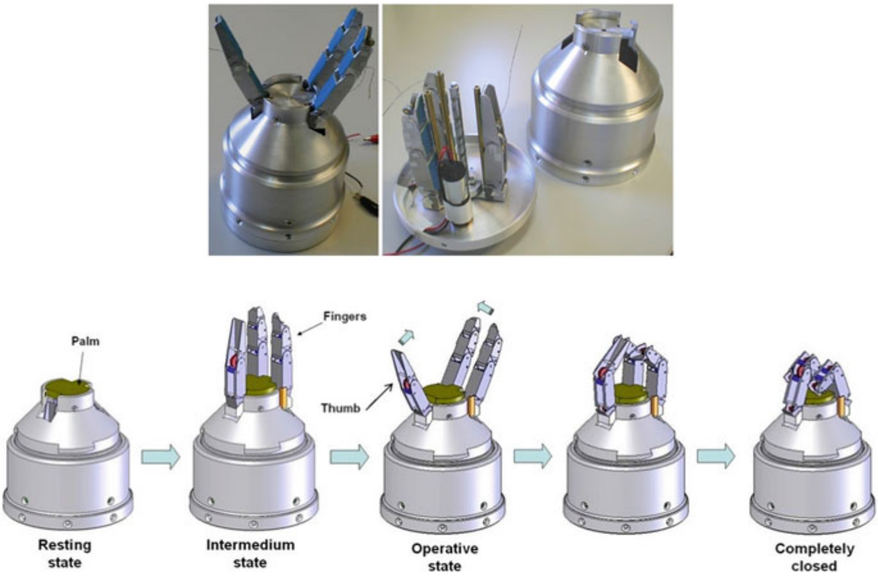


Fig. 11 RL1 Hand and its states

objective of the cradle is to help the driving system of the RL1 to reach all the positions and tasks needed by rotating the energy transformer in just one way. This allows the hand to pass from a standby state to and operative one, ready to hold an object through different states transforming mechanisms. It is possible to see an already developed RL1 Hand in Fig. 11. This group of mechanisms make the RL1 Hand driving system to be formed by a unique Multi-State Actuator that allows the Hand to pass through different positions, since the resting states inside the anchor until the fingers and thumb driving position, necessary to hold an object. It is also possible to see those different positions. Finally, Fig. 12 shows the RL1 materializing holding tasks for different objects with different shapes and sizes.

RL2 Hand

The RL2 Hand has been designed to be mounted on a new version of the MATS Robot, The ASIBOT Robot Arm that differs from the previous version by small changes at the control system, sensor system and the capacity computing resources, without changing the mechanical structure. For that reason, the predetermined requirements for the RL2 Hand are the same as the ones detailed for the RL1 Hand. The RL2 Hand was intended to enlarge the functionality of the Hand referring to shape and size of the objects to be held, basing the entire project on the experience obtained with the RL1 Hand. The RL1 Hand was able to hold in

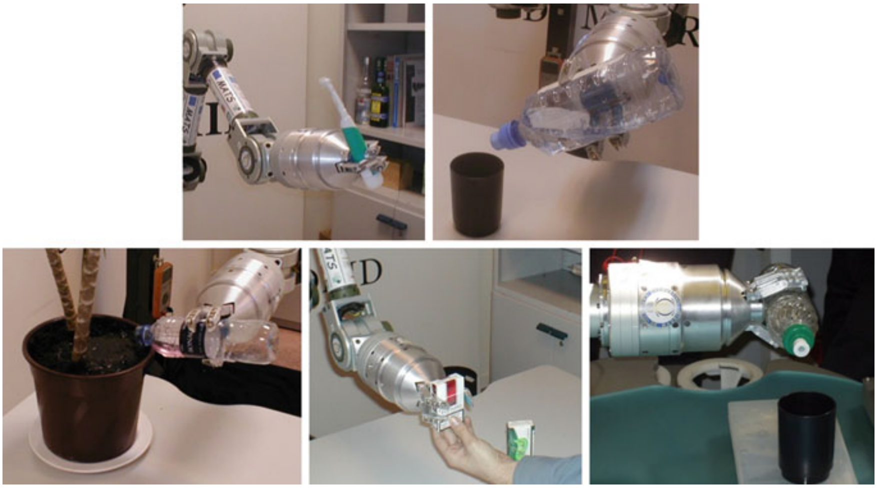


Fig. 12 RL1 Hand with different types of grasp tasks

a correct way fully or partially enveloped object, such as cylinders, elongated prisms, etc. However, in what plane objects referred (i.e., books or boxes) or elongated cylinders, in which the section was below a certain threshold (i.e., a pen) the efficiency of the holding was uncertain and unstable. As the mentioned objects are daily used, it was one of the main purposes of the RL2 Hand to better the holding liability. To enlarge the number of phalanges of a robotic hand higher the probabilities of reaching a higher number of contact points between the robotic hand and the object. That means that improving the holding security without having the independent control over the degrees of freedom might be only useful for a determined kind of object sizes and shapes. The RL2 Hand has a new configuration of the elements as it allows the possibility of taking some of them out without decreasing the holding liability. However, it gives more functionality to the hand by the adding of new passive mechanisms. The strength transmition system through tendons and pulleys used for the RL1 Hand, was really successful. However, it was inefficient because only one portion of the strength exercised by the engine reached every part of the joints. This point was observed in the new design improving the efficiency of the transmission helping the engine energy savings and the re-positioning of the pulleys inside the finger (Cabás et al. 2006). Two negative phenomena related to the Underactuated robotics hands are the roll back phenomenon and the ejection phenomenon (Birglen et al. 2008).

The roll back phenomenon appears at Underactuated robotics hands that have many Degrees of Freedom (DOF) and for design issues the last phalange is able to make an elevated par before the object gets tightened in a balanced way in relation with the rest of the elements. It slides over the object and starts to close over itself without producing a touching point and making the whole object holding totally inefficient. On the other hand, the ejection phenomenon is produced when the last

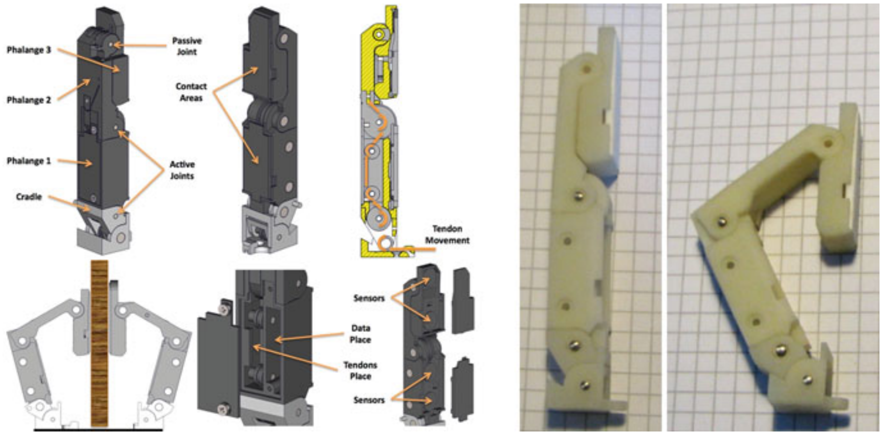


Fig. 13 RL2 Hand′s finger configuration

phalange does not reach the roll back because it stops in a point determined by the object but cannot make an effort over the object. The problem lies on an instable and uneffective contact point. For that reason, depending on the position of the object to be held, it can discard. These two phenomena were identified with certain objects of the RL1 Hand and should be fixed at the RL2 Hand. One of the potential solutions was to enlarge the size of the last phalange but the limit of the short space available the only alternative was to reduce the size of the phalanges and reducing the size of the objects able to be held. The other option, which was finally taken, was to eliminate the last phalange and to balance the length of the other two. The new configuration of the interior of the RL2 Hand fingers is shown in the Fig. 13. The RL2 Hand finger has three joints, two active and one passive. This last passive joint is the one that allows the RL2 to have more functionality and efficiency when holding plane objects like books and boxes. When the fingers begin the closing step they also locate themselves in a way that last phalange rotates in the contrary way putting the contact surfaces parallel.Inside the finger, as it can be seen in this case, the tendon only reaches the second joint to give movement to the second phalange.Another important improvement added by the RL2 Hand finger is the hosting of the two strength sensors on the contact surfaces, under the Hand. This configuration allows not only to measure the strength reached by that surface but also to calculate the longitudinal position of the contact point through the value each phalange sensor takes. This has been an important improvement for the knowledge and the learning of repetitive tasks. In order to have the sensors signal or to be more precise, to have the cabling that connects the sensors to the control system, out of damage danger or getting broken with the tendon or pulley’s internal movement, the interior of each phalange has been longitudinally divided in two parts: one of it has all the signal cabling and, the other has all the pulleys and necessary mechanisms for the joint driving.

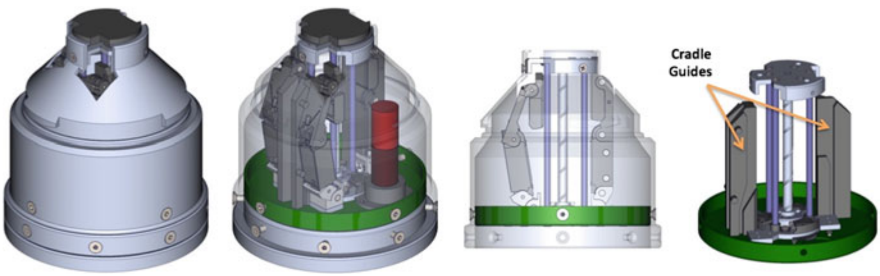
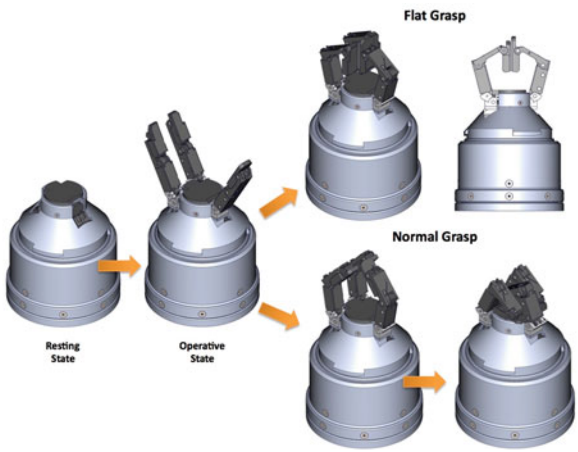


Fig. 14 Location of the RL2 Hand inside the docking

Fig. 15 States of the RL2 Hand



As in the RL1 Hand, the fingers and the thumb of the RL2 Hand are located on a cradle which helps the hand to position inside the anchor with a configuration and then, once it leaves it, to locate in a holding tasks position. In this case, the cradles do not need to be driven. They are free and are taking different positions every time a finger leaves the anchor. To make this possible there are some guides that help the cradles to slide and position each finger into the necessary configuration (Fig. 14). One of the main reasons why this design has been chosen is the better use of the free space inside the anchor. Fingers inside the anchor are in a particular position and have its joints rotating. However, the fingers keep a small chamfer in its last phalange to help it not to go out to the anchor's exterior surface. On the other hand the objective of doing free cradles is to eliminate the middle state of the hand when it is taken out from the anchor, saving time and internal mechanisms (Fig. 15). Another improvement this design presents is the adding of three strength sensors for the palm in a way that it does not only help to know the value of the strength done with it, but also its position on the design depending on the strength done in each point.

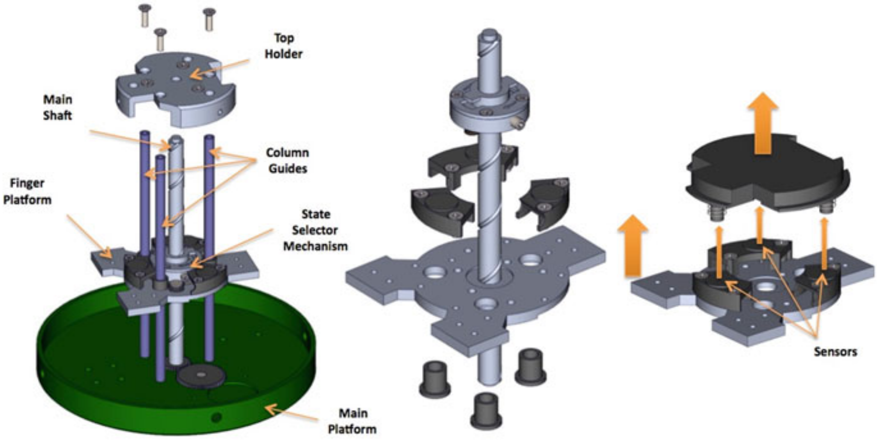


Fig. 16 Drive system integrated inside the RL2 Hand's structure

Fig. 17 Final design of the RL2 Hand

These three sensors are located in the states mechanism selector, the Multi-State Actuator, which interacts with the palm and is taken out to cover the ASIBOT contacts, when the Main Platform is removed. The extraction system of the RL2 Hand fingers keeps almost intact its functioning philosophy because the results obtained at the RL1 Hand has been successful. In this particular case, the design has been only focused on the energetic performance of the energy transformer. Pulleys have been located in all the tendons way avoiding them to pass over surfaces that can create unnecessary friction. In Fig. 16, it is possible to see the changes done for this last design and a detail of the pieces that compound it. The final result of the design is shown in Fig. 17.

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Mobile Robots

Ángel Gaspar González Rodríguez and Antonio González Rodríguez

Abstract This chapter presents an introduction to mobile robots in the field of the service robots, paying special attention to the mechanical structure of wheeled, legged, hybrid and tracked robots. The issues regarding to the maneuverability and capability of overcoming obstacles are discussed for the wheeled robots. A classification of the wheeled robots is made according to the way they are steered and driven, exposing the forward kinematics equations for every basic scheme. The common characteristics of hybrid and tracked robots are also presented, together with their advantages and drawbacks. A classification of legged robots is also included, focusing mainly on the structure of the leg and discussing relevant issues regarding controlability and efficiency.

1 Introduction

Nowadays, most of the robots are found in the industrial activity, especially as fixed robot manipulators. When they began to be incorporated to the factories, also did the mobile robots as automated guided vehicles (AGV), transporting goods and tools along a predefined trajectory. Cravens Company installed the first one in 1954 at Mercury Motor Express in Columbia, SC. However, in present days most of the applications for the new mobile robot designs belong to the service field. This fact has given rise to identification between robot manipulators (and parallel

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N. E. Nava Rodríguez (ed.), *Advanced Mechanics in Robotic Systems*,
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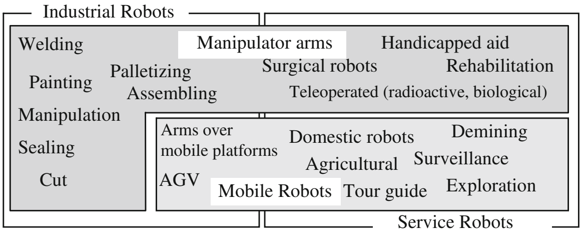


Fig. 1 Distribution of robots according to their application (industrial or service robots) and displacement capabilities (manipulator arms or mobile robots)

robots) as the unique industrial robots, and on the other hand between mobile robots and service robots, although important and consolidated exceptions exist (see Fig. 1). This way, most of the industrial robots are parallel robots or robot arms in one of these possible serial configurations: Cartesian, cylindrical, anthropomorphic robots or SCARA as the most important ones. However, they can be found out of the industrial activity, as flight simulator (Stewart 1965; Pisla et al. 2009), surgical systems like daVinci system, aid to individuals with disability (McCaffrey 2003), in rehabilitation tasks (Harwin 2003), tele-manipulated in dangerous radioactive or biological manipulation. As defined by the International Federation of Robotics, service robots are the ones installed in non-manufacturing operations. However, this term is more commonly applied to robots operating out of the industrial activity. Service robots usually include movement capacities, and therefore mobile robots find its main source of application as service robots. There are numerous configurations for mobile robots, each one more adapted to the environment in which the robot must operate. Basically there are flying (Howard and Kaminer 1995; Chao et al. 2007), underwater (Yuh 2000; Terada 2000) and terrestrial robots, and among these ones, hopping (Raibert et al. 1984), climbing (Nagakubo and Hirose 1994; Fu et al. 2007), but mainly wheeled, tracked and walking robots, which will be the objective of this chapter. Figure 1 shows some examples of industrial and service robot applications (García et al. 2007).

Mobile robots have not spread in the same extent as the industrial robots, whose absence is not understood in several applications of the industrial activity. The industrial robot success in replacing the human operator is mainly due to the cost reduction, which is a factor that has not been shown so clear when projecting or acquiring a mobile robot. Fortunately, there are a growing number of exceptions like the autonomous transportation systems, the robots for surveillance, domestic cleaning robots or the last generation of humanoid ones. Disregarding the economical factor, the mobile robots have been successfully installed in applications with environments that are inaccessible or hazardous for a human being (Apostolopoulos and Bares 1995), or in tasks with very demanding duty cycle or a very high fatigue factor. In these situations, the mobile robots can be fully autonomous if the system can operate without a continuous external human control, or semi-autonomous if they require the guidance of an operator but with the capability of accomplishing certain tasks such as obstacle avoidance.

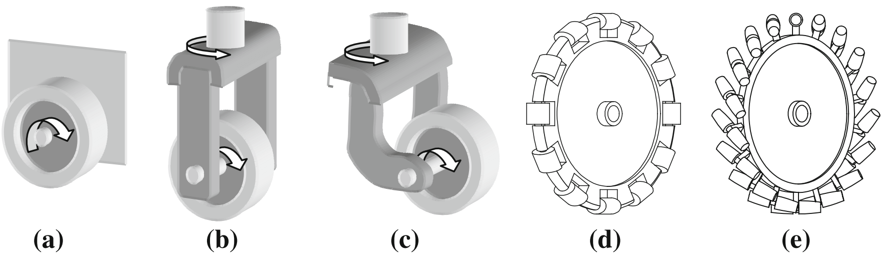


Fig. 2 Conventional wheels: **a** Fixed wheel. **b** Centered orientable wheel. **c** Off-centered orientable wheel. **d** Swedish wheel 90°. **e** Swedish wheel 45°

2 Wheeled Robots

Wheels are an unnatural but highly efficient means of locomotion, and it is the preferred method to use in mobile robots when no obstacles are present in the environment in which the robot is going to operate. Their good performance lies on their simple control to move and maneuver, its high capacity load and efficiency, and reduced cost compared to other solutions.

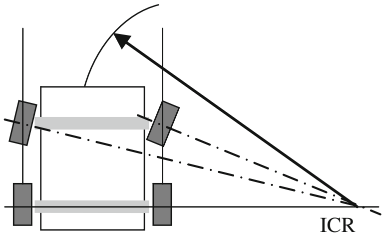
Type of Wheels

Mobile robots use three basic types of conventional wheels (Campion et al. 1996) (see Fig. 2):

1. Fixed wheels, in which the center of the wheel is a fixed point of the frame, where only rotation around the horizontal axle is permitted.
2. Centered orientable wheels, which allow the motion of the wheel plane around a vertical axle passing through the center of the wheel. The orientation is usually active, i.e., driven.
3. Off-centered self-orientable wheels, also known as caster or castor wheels, which are orientable with respect to the frame, although the wheel plane rotates around a vertical axle which does not pass through the center of the wheel. If the wheel is not properly headed, a tangential force appears at certain distance from the wheel center. It gives rise to a torque that orientates the wheel plane in the direction of the tangential force, avoiding the lateral slipping.

Besides these conventional wheels, special wheels can be used to obtain an omni-directional motion. This is the case of mecanum or Swedish wheels, with small passive free rollers located at the outer rim of the wheel, which permits the lateral motion of the wheel (Campion and Chung 2008). Their axis of rotation is parallel to the wheel plane, as in the Swedish 90° model, or it can make an intermediate angle, as in the Swedish 45° model, for a smoother performance.

Fig. 3 Instantaneous center of rotation or curvature of a wheeled vehicle



Regardless of the wheel type, for a wheeled robot to exhibit a rolling motion, every wheel must follow a circular trajectory around the same point, that is known as instantaneous center of curvature or rotation (ICC or ICR at Fig. 3). If the vehicle follows a linear trajectory, this point is at the infinity. The orientation of the steering wheels determines the proximity of the ICR and in turn, the vehicle orientation. The rotational speed of the wheels must be varied accordingly and the degrees of freedom (DOF) are reduced to the vehicle speed and orientation.

Since the vehicle situation on the surface (often referred to as pose) is defined by a two-coordinate position and an orientation, it is not possible to change arbitrarily these values nor every path is achievable. In a simplified way, the term non-holonomic is applied to the robot with less controllable degrees of freedom than the necessary to define its pose, i.e., its position and orientation. In a non-holonomic vehicle like a wheeled one, unless slippage occurs, the wheels cannot move in a direction parallel to the axis. This means a constraint in the lateral motion that decreases the degrees of freedom (Bekey 2005). As in the case of a car parking in parallel, its state or pose is determined by the path followed to reach it, and it is possible to get to any state by performing a sequence of maneuvers, whose number and amplitude depend on the environment clearance and the vehicle characteristics.

Different Ways to Steer a Wheeled Vehicle

There are different ways of driving a wheeled vehicle (Dudek and Jenkin 2000).

Differential Drive

It consists of two wheels mounted on a common axis driven by different motors. One or two undriven wheels, usually of the type of caster wheels, are included for stability. The magnitude and sense of each wheel velocity determine the kind of motion to be performed: if the speed of both wheels is the same, the robot moves linearly; if the speed is the same in magnitude but with opposed sign, the robot rotates in place; in any other case, the robot rotates with an angular speed ω_t around the ICR whose distance R to the robot is obtained from Fig. 4.

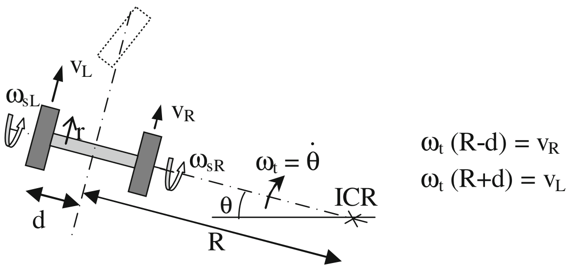


Fig. 4 Differential drive kinematics

$$R = \frac{d(v_L + v_R)}{v_L - v_R} \quad \omega_t = \frac{v_L - v_R}{2d} = \frac{r(\omega_{sL} - \omega_{sR})}{2d}. \tag{1}$$

The high steering capability of differential drive vehicles allows them to move in narrow and curved environments as in urban pipelines. Its major drawback, deduced from the previous expression, is the fact that the orientation θ of the vehicle is very sensitive to the difference between both wheel speeds. Examples of differentially driven motors are the low-cost indoor robots as the Pioneer P3-DX, the Kephera or the TuteBot, and the all-terrain ATRV from iRobot, with a more rugged configuration.

Tricycle

A different three-wheel configuration can be obtained if the middle wheel is steered and driven. This is a less complex configuration although the absence of differential drive limits its maneuverability. From Fig. 5, the distance R from the ICR to the tricycle axis as well as the turn velocity ω_t can be obtained

$$\begin{aligned} R &= \frac{d}{\tan\alpha} \\ \omega_t &= \frac{v_s}{d}\sin\alpha = \frac{\omega_s r}{d}\sin\alpha \end{aligned} \tag{2}$$

where v_s, ω_s and r are respectively the linear speed of the front wheel, its angular speed and its radius.

Synchronous Drive

A synchronous drive vehicle consists of several wheels (typically three), equally spaced, each of them capable of being driven and steered. All the wheels point in the same direction and rotate at the same speed, which means that it only has two degrees of freedom. However, due to its high maneuverability that allows the robot to control its orientation directly, it behaves as a holonomic robot Fig. 6.

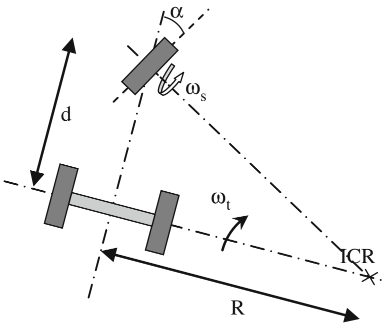


Fig. 5 Tricycle configuration in which the front wheel is steered and driven

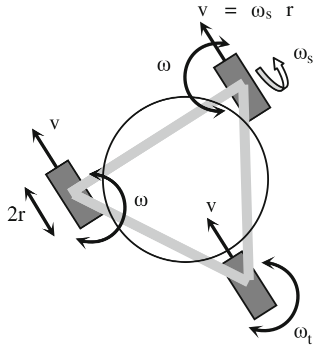


Fig. 6 Synchronous drive kinematics. Wheels turn at ω_t in unison and rotates at the same speed ω_s

Omni-directional Drive

It includes Swedish wheels to obtain a holonomic performance with three DOFs. An example is the platform Uranus with four Swedish wheels 45°, in which only three of them can be independently driven.

Ackerman Steering

Also known as kingpin steering, it is the kind of steering commonly used by automobiles and in large robots. Its schema is the one represented in Fig. 7. In order to avoid lateral slipping the axis of the steering wheels cannot be parallel, and must point to the ICR. This is achieved by turning the inner wheel through a higher angle than the outer one ($\alpha_L > \alpha_R$). Assuming that in these conditions the vehicle turns through an angle α_{eq}, then the system is defined by

$$\left.\begin{array}{c} R+\frac{L}{2}=d\cot\alpha_L \\ R-\frac{L}{2}=d\cot\alpha_R \\ R=d\ \cot\alpha_{eq} \end{array}\right\} \Rightarrow \left\{\begin{array}{c} R=\frac{d}{2}(\cot\alpha_L+\cot\alpha_R) \\ \cot\alpha_L-\cot\alpha_R=\frac{L}{d} \\ \cot\alpha_{eq}=\cot\alpha_R+\frac{L}{2d} \end{array}\right. . \quad (3)$$

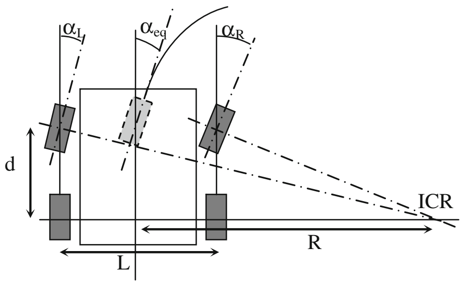


Fig. 7 Ackerman steering kinematics

The maximum angle α that the steered wheels can turn has a limited value, which in turn limits the minimum radius of curvature and hence its maneuverability.

Wheeled Robots in Rough Terrains or With Obstacles

There are two main techniques to allow a wheeled robot without articulated legs to move in rough terrains or with obstacles.

Low Inflation Wheels

Wheels by itself have certain capability of overcoming obstacles, which depends basically on two parameters: diameter and inflation pressure. The height of the obstacle that the wheel is able to overcome is proportional to the diameter. Nevertheless, a larger wheel reduces maneuverability and can impede the support in a step tread. With regard to the inflation, a lower pressure allows the generation of higher contact forces in the obstacles edge (Lawn 2002). In contrast, the efficiency is drastically reduced. To increase the efficiency and maneuverability, several prototypes have been built combining low inflation wheels with either tracks or high pressure wheels (Uchida et al. 1999; Hirose et al. 2001).

Cluster of Wheels

A cluster of wheels consists of a set of wheels mounted on a bar attached to the chassis by means of a shaft that permits the relative rotation. This rotation successively locates the wheels in the following step tread or in the higher flat part of the obstacle. Figure 8 shows a prototype with a second cluster to improve the stability. Following this research line, different prototypes has been developed, like the wheelchair Freedom from Tomo Co. Ltd, the wheelchair IBOT 3000 or the design presented in (Lawn and Ishimatzu 2003).The advantages of the clusters are: fair rolling efficiency, comfort and stability when negotiating a step (dislike the

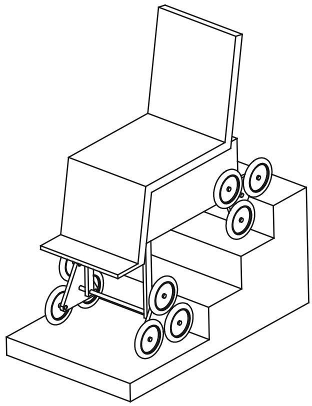


Fig. 8 Wheel chair with double wheel cluster (source Tomo Co. Ltd. And Tamagawa University)

tracks). The more important drawbacks are high value of the torque driving the cluster axle, the high number of motors and brakes, as well as the complex trajectory of the cluster center of rotation, which makes the system control more complicated.

3 Tracked Robots

Tracks have been so far the method that to a higher extent has been identified as all-terrain means of locomotion. Tracks provide robots with the ability of overcoming steps and obstacles with different geometries and moving in very rough terrains without increasing the control complexity.

They were initially conceived to propel tanks during the First World War and later its use has been spreading to numerous fields. Nowadays they have become irreplaceable in much of the heavy machinery used in civil engineering. Their application in robotics is mainly focused on military purposes or hazardous environments (Trevelyan et al. 2008; Zhao et al. 2008; Welch and Edmonds 1993), for inaccessible place explorations and in platforms/chairs for handicapped people (Lawn et al. 2001; Hirose et al. 1992). Tracked robots are differentially driven vehicles that allow turning with lower radius of curvature. However, slippage on the ground is necessary in order to turn the vehicle. On the other hand, in order to overcome obstacles, high friction coefficients between track and ground are required. Therefore, treads may wear rapidly and must be replaced frequently (Bekey 2005). Other disadvantages are lower speed than wheeled robots, and the fact that they can deteriorate the surface when moving in urban or domestic environments. In case of transporting elder or disabled people, the lack of primary dampers reduces the user comfort. Additionally, the stability of tracked robots when negotiating the descent of a step is temporarily lost, which may cause uncertainty and panic.

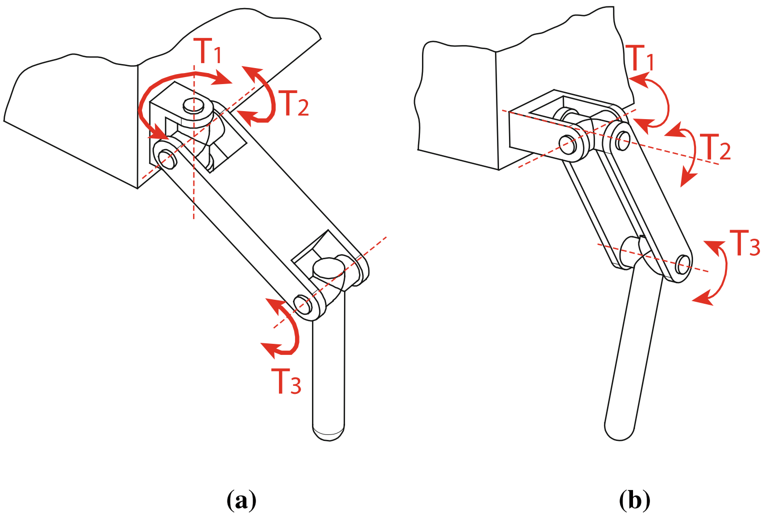


Fig. 9 Articulated legs consisting of three rotational joints: **a** insect-like. **b** mammal-like

4 Legged Robots

Legs are the most important and active member among the ones that improve the mobility of robots. Unlike wheeled robots they must be able to move in soft and rough terrains (like mud, sand, forest, rocks) or overcoming obstacles like steps. With regard to the configurations of legs for walking robots, there are three types of research lines: articulated legs, passive-dynamic legs, and decoupled configuration legs.

Articulated Legs

The vast majority of the current legged robots use very simple leg schemes, which are made up of a chain of links joined by joints according to one of the two forms shown in Fig. 9: insect-like legs and mammal-like legs. The legs of reptiles have a similar configuration to mammals, although the parallel axes (labelled as *T2* and *T3*) belong to very separated vertical planes and hence they undergo higher torques (Guardabrazo and Gonzalez de Santos 2004). Reptile-like robots also require an articulated body to keep balance during the crawl movement (Ishihara and Kuroi 2006). Although different types of actuators can be found, most of biped robots use the scheme shown in Fig. 9b in which electrical motors drive rotational joints. As reproduced in Fig. 10a biped robot legs require a relatively wide and flat foot to provide static stability and improve the dynamic one. Unless a penguin gait is not a concern (Collins et al. 2005),

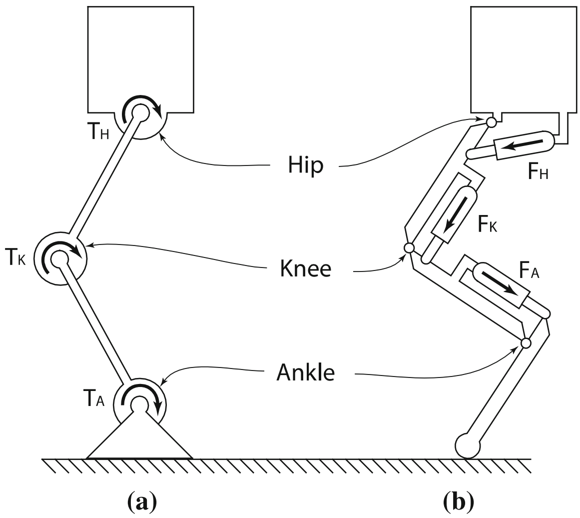


Fig. 10 Conventional schemes for articulated legs: **a** with rotary motor (Asimo). **b** with linear actuators (Big-Dog)

the clearance of the foot must be accomplished by means of an ankle, with a rotational joint whose axis is perpendicular to the sagittal plane.

In order to keep balance a lateral movement is required that is performed by a set of two joints per leg (not shown in the figure), one in the hip and another in the ankle, whose axes are parallel to the movement direction. This high number of joints allows an extended set of movements and activities, e.g., walk, run, climbing stairs, dance, fight, play football. Despite their current application as toys or research bed tests, biped robots are intended to operate as assistance robots. Since they must be in close interaction with humans, these robots must, for psychological reasons, mimic the human appearance, configuration and movements. This is because legs for biped robots have an articulated configuration like humans, disregarding factors like autonomy that is not a concern in domestic applications. A different type of movers is included in the Big-Dog that uses hydraulic linear actuators as it shown in Fig. 10b. Since it is a quadruped, the ankle answers other purposes, mainly compliance and reaction absorption. Articulated legs have an important problem related to the size of actuators. If the robot wants to raise its body, the robot must exert torques T_K and T_A (or forces F_K and F_A) in knee and ankle, that can be as high as

$$T \approx L_L m\,\mathrm{g} \tag{4}$$

For a certain value of mass m and link length L_L. Due to the coupled structure, during stance, transfer, leg ascent or leg descent, the robot must operate all of the leg actuators. However, the horizontal and vertical movements have very different characteristics for a creature with legs, whether robot or animal: vertical movements require a lot of strength to bear the weight of the creature, and the horizontal movement does not need as much strength but a high speed to increase the

step frequency. This way, all of the actuators are oversized to have both high values of torque and speed, leading to increased power losses and weight. Since current technology determines the weight and power of electric motors, legged robots driven by electrical actuators are heavy and with low capacity. Big-Dog addresses these limitations by including hydraulic actuators.
Another drawback is that these structurally simple configurations require, however, a complex calculation of the inverse kinematics to accomplish the desired foot trajectory. In addition, the unit control must split the trajectories for all of the involved motors and continuously regulate their speed to generate this path. The movement should be accurate because a small error of a few degrees means centimetres in the leg support, which would lead the robot to get out of balance and fall. The control task became so complex that the step frequency cannot be very high, and therefore, the walking robot is much slower than the legged animals with similar sizes. In consequence, schemes using articulated legs lack reduced efficiency, increased control complexity and over sizing. Two research lines aim to contribute more-efficient designs: passive-dynamic walkers and decoupled configurations.

5 Passive-Dynamic Walking

Walking is a repetitive movement in which every bar of the legs accelerates, decelerates and stops at every step. Robots spends energy every acceleration and usually also every deceleration, leading to important power losses and reduced efficiency. There are, nevertheless, examples of high efficiency legged artificial locomotion during last years. Most of them are based on the concept of passive-dynamic walking, which was developed by McGeer in the late 1980s. First walkers were coupled inverted pendulums that descend a shallow slope due to the transference between gravity energy and inertia (McGeer 1990a). By powering some of its joints, the robot can walk in flat surfaces. For example, a driven ankle allows the supported leg to rise, thus providing enough gravitational energy to perform a new step as it were walking down a slope. Further versions add knees to the initial design. As explained in McGeer (1990b) there are two reasons for this change. First, knees give rise to a more natural gait, and this analogy facilitates the study of the walking cycle. Second, flexing knees allows the robot to bring forward the leg that is in the air without help of motors. Additional examples of passive-dynamic walker are found in Collins et al. (2005). In McGeer (1990c), the scheme of an efficient running robot was presented. To allow the vertical movement, each of the two legs consisted of two bars joined by a telescopic joint with linear springs. A rotational joint with a torsion spring attached the legs to the body, creating an alternative movement. Adjusting the stiffness of all of the springs the gait frequency was accordingly modified, taking into account that the frequency varies with the square root of the stiffness. In addition, actuators must be included to allow the robot to overcome obstacles. First solution use pneumatic actuators, most of them based on the McKibben design

(Schulte 1961). Pneumatic actuators are light and simple, but they need complex valves and compressors (or a tank), drawbacks that impede their use in e.g., prosthesis. These systems are also difficult to control. One interesting robot with pneumatic actuators is Lucy, developed in Brussels (Vanderborght et al. 2006). A different type of artificial muscles are the ones based on electroactive polymers (EAPs), whose shape is modified when they are applied a voltage, as reported in Duncheon (2005) and Ashely (2003). They exhibit the ability to undergo a large amount of deformation. However, the preferred solution consists of a combination of a DC motor and an elastic element (Pratt and Williamson 1995). The system stiffness is adjusted to its maximum value for operations where a direct drive is needed, e.g., to surpass an obstacle or to keep balance when the robot is stopped. During normal walking in a flat surface with an optimal efficiency, the joint stiffness is adjusted to the gait frequency. There are different approaches that are summarized in Ham et al. (2009).

6 Decoupled Configurations

Another solution to improve efficiency starts from the fact that the horizontal and vertical movements have different characteristics in terms of torque and speed. Therefore, it is more-efficient to decouple these movements and drive them with different kind of actuators. Typically, a high-ratio gearbox is used for vertical movements and a more direct drive for the horizontal movement. Additionally, decoupling reduces power losses since actuators that move do not withstand the weight and vice versa (Kar 2003). Besides the more suitable actuator selection, a decoupled configuration simplifies the inverse kinematics calculation that in turn, simplifies the trajectory control, especially during the support phase, and leads to more continuous and efficient trajectories to be described by the actuators. As shown in Fig. 11 decoupled configuration has been traditionally achieved by means of SCARA configuration and two-dimensional pantographs. Their sequences or joints are respectively rotational-rotational-prismatic and rotational-prismatic-prismatic. The structure of Fig. 11b assembles a mammal configuration. A preferred, but not necessarily better, configuration mimics the insect or reptile structure and movement, operating the rotational joint around a vertical axis. Climbing robots like the ROWER, the REST, or the tethered ROBOCLIMBER use a SCARA configuration. Many of the Hirose's robots TITAN, the tethered climber DANTE II or the MECANT use a two-dimensional pantograph. The hybrid Wheel leg of Guccione and Muscato (2003) includes a similar performance (rotational-prismatic-prismatic) although without using a pantograph. The leg mechanism of Gonzalez Rodriguez et al. (2009) also falls into the decoupled leg mechanisms but with a different structure. It has been designed in order to obtain fast and easy controlled walking operation in obstacle-free environments. A wide workspace allows the leg overcome high obstacles. The leg structure avoids joint locking and is not sensitive to reactions in any direction. According to the scheme

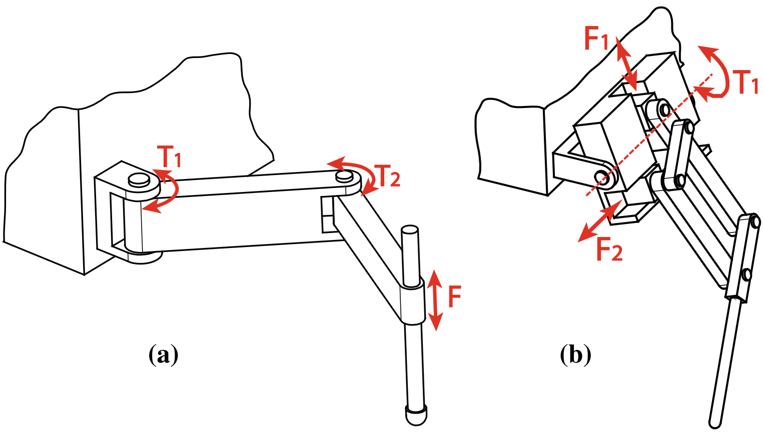
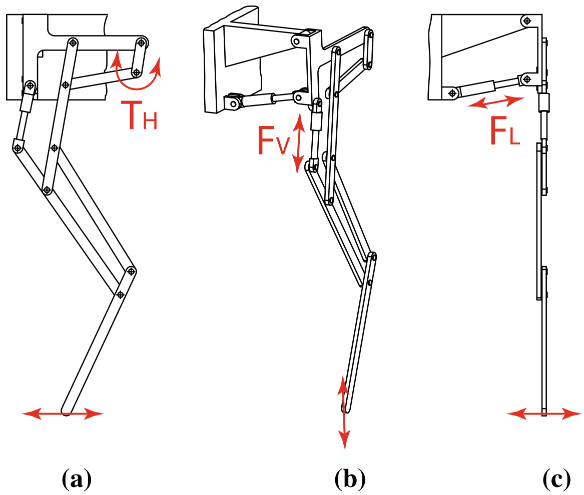


Fig. 11 Decoupled configurations: **a** SCARA. **b** two-dimensional pantograph

Fig. 12 Scheme of the leg and actuator for the corresponding movements: **a** horizontal. **b** vertical. **c** lateral



of Fig. 12, two DOFs are required to obtain horizontal (a) and vertical (b) motion of the leg in the saggital plane. This mechanism is synthesized to provide an approximate straight trajectory segment during the support phase, only operating over one actuator, with the other being inactive. The third DOF allows rotating the plane of movement with respect to an axis parallel to the movement direction, and it is driven by a third linear actuator. It is necessary to maintain stability and to make the robot turn. Once the vertical, lateral and horizontal movements of the leg

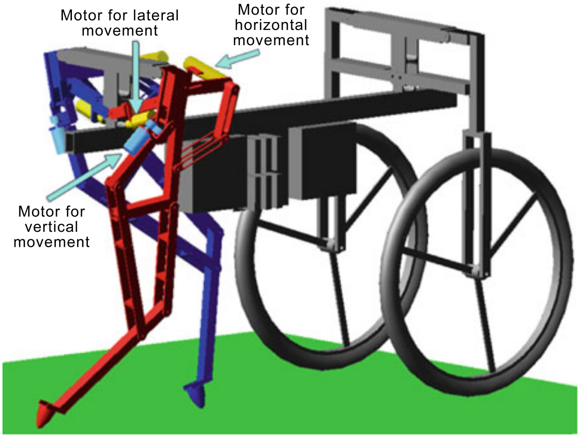


Fig. 13 Hybrid locomotion system with two legs and two wheels

are decoupled, a properly selected reduction gear allows using motors with less power and weight.

The leg performance is improved by adding a mechanism that obtains proportionality between the speed in the horizontal DOF and the horizontal foot speed.

7 Hybrid Systems

Hybrid robots are machines that combine articulated legs and wheels with the aim of exploiting the capabilities of both wheeled and legged robots. Two research lines can be differentiated: legs and wheels, and leg with wheels.

Hybrid Systems Using Legs and Wheels

This solution typically presents the form of a biped structure that has added passive wheels in the rear part to increase stability and the capacity load (see Fig. 13). The leg configuration can follow any of the schemes presented in the previous section. Different factors can lead the designer to choose this solution: economical reasons since it replaces two or more legs by wheels; to simplify the control that implements the robot gait; to increase the capacity load; and to increase the robot speed. In contrast, this solution limits the height of the obstacles that the robot can overcome and the roughness of the terrain through which the robot can move. Examples of this type of hybrid robot are the

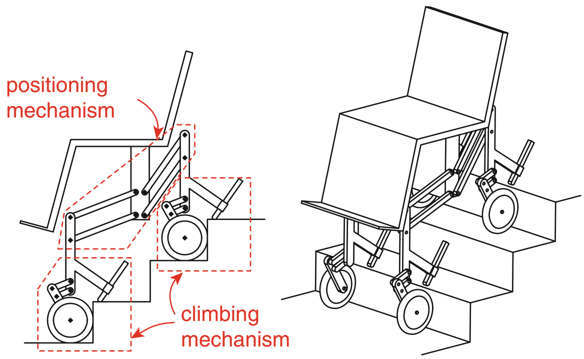


Fig. 14 Hybrid locomotion wheelchair with two mechanisms to negotiate a stair

prototype presented in Guccione and Muscato (2003), Cubero (2000) and Germann et al. (2005).

Hybrid Systems Using Legs with Wheels

This method consists in including wheels in the extremes of the articulated legs, in a similar way to human skater. To this scheme belongs the prototypes presented in Aarnio et al. (2000), Grand et al. (2004) and Siegwart et al. (2002). The common drawbacks of these models derive from the numerous degrees of freedom to drive and control. It results in increased complexity, weights and costs. The Roller-Walker from Hirose and Takeuchi (1996) partially address these drawbacks, adopting two means of locomotion: walking on roughness terrains or with obstacles; and skating on passive wheels when moving on flat surfaces. This structure avoids the traction, steering and braking systems for the wheels, thus reducing weight, volume and cost.

8 Other Hybrid Locomotion Systems

To the group of hybrid system also belong other structures like the RHex or the ASWARD, which respectively use one or several compliance passive arms attached to a driven rotational shaft. Figure 14 shows a hybrid locomotion wheelchair (Gonzalez Rodriguez et al. 2007), designed to negotiate steps and stairs by means of a climbing mechanism attached to each shaft. A different mechanism is responsible of keeping balance and improving the performance when climbing stairs.

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Parallel Manipulators

Erika Ottaviano

Abstract Nowadays parallel robots have been extensively studied and new prototypes have been patented and commercialized for a large number of industrial and non industrial applications. A recent trend in parallel manipulators concerns with the emerging area of modular re-configurable parallel robots. This class can not only be referred to classical parallel manipulators, but also to cable-based systems. Recently, a new class of parallel robots has been developed, namely the cable-based parallel ones, and they have attracted the attention of the Robotics community because of their potential advantages over conventional parallel robots. In this context, a survey is presented on recent developments on modular re-configurable parallel robots, both classical manipulators and cable-based ones. A case study of a re-configurable cable-based parallel manipulator is presented.

1 Introduction

Recent trends in parallel manipulators show a growing interest in modular re-configurable parallel robots. This class can be referred either to classical parallel manipulators, but also to cable-based systems. In this context, issues related to modular re-configurable parallel robots are presented, both referring to classical ones and cable-based manipulators.

A Modular Re-configurable Robot (MRR) consists of a number of discrete modules, which are capable of being mechanically and usually electrically connected with each other (Yim et al. 2004). A configuration is defined as a particular arrangement of connectivity between independent modules. A configuration can be represented in

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N. E. Nava Rodríguez (ed.), *Advanced Mechanics in Robotic Systems*,
DOI: 10.1007/978-0-85729-588-0_4,

graph form, called configuration graph in which, the vertices represent the modules and the edges represent the connection between the modules (Asadpour et al. 2008). While the number of different varieties of modules in a single MRR is usually small, the capabilities of a single module, which may only have one active degree of freedom (DOF), are modest, the combination can form an arbitrarily complex structure. Furthermore, it may allow to obtain a huge number of different robots with different application starting from the same set of modules (Agrawal et al. 2001).

Theoretically, a well designed set of modules can lead to the construction of robot for almost any purpose That provides a potential for cost savings in industrial frame. In fact, while in bigger companies with high lot sizes highly specialized systems can be used, smaller and medium sized companies can make profit of re-configurable robots (Bi et al. 2006). The investment cost in purchasing a robot is worth it, because it can be re-configured at relatively low-cost according to the task (Modungwa et al. 2008). This is not the only benefit from designing a modular robot, in fact, it gives the possibility of re-configuration, which allows modules connecting (or docking) and disconnecting according to the needs. Referring to the above-mentioned property, the mechanical interface between any two modules can be electrically actuated, i.e., the modules can self-connect and self-disconnect under the robot's own control and thus completely changing its fundamental structure (Stechert and Franke 2007).

Self-reconfiguration is a transition between two configurations by a series of elementary actions such as connect and disconnect (Slee 2006). Therefore, if conventional robots are usually built on purpose for performing a limited number of tasks in one specific environment, i.e., assembling, cleaning, welding, delivering; modular re-configurable ones allow changing their configuration in order to adapt to the environment and task changes. The advantages of developing re-configurable systems can include adaptability, reusability, convertibility, compactness, fault-tolerance and emergency behavior.

Modular robots can be divided into two categories based on their mechanical design: homogeneous and heterogeneous systems (Slee 2006). In first type, all modules are mechanically identical. One of the advantages of homogeneous systems is that all modules can be replaced by any other module, if they fail. Examples of homogeneous modular robots are the M-TRAN and the ATRON robot.

Heterogeneous modular robots have at least two mechanically different modules and the most common ones have two different modules. Examples are the Tetrobot and SMAnet robots. In chain-based systems it may be an additional passive module providing branching of chains of active modules, like the PolyBot. However, the CKBot is a heterogeneous chain-based system which has both different active and passive modules and depending on the functionality the modules also provide branching.

The concept of modularity has been used in the design of serial-type industrial robots for flexibility, ease of maintenance, and rapid deployment.

A classification of modules can be based on their functionality (Yang et al. 2001):

- Structure module—passive module which adds structural features.
- Actuated module—active module, which enables the robot to perform tasks, such as locomotion and manipulation.

- Sensor module—provides sensory inputs about the environment.
- Power module—provides energy to the robot.

Research into re-configurable systems is primarily active in Robotics. Examples of re-configurable robots can be found in applications including planetary exploration, undersea mining, search and rescue and other tasks in unstructured, unknown environments (Hjelle and Lipson 2009; Agrawal et al. 2001; Lee and Sanderson 2001; Yim et al. 2004). Another challenging application is assisting robots for aged care or disabled people. These robot can fetch, carry and assist with walking and motion (Chugo et al. 2008).

Another interesting classification of modular re-configurable robots has been proposed into three categories (Xi et al. 2006): self-assembly, self configuring and manual configuring. Self-assembly robots are those with the highest level of re-configurability because they can detach from and attach into a robotic system automatically. Self-configuring robots cannot perform self-assembly. However, they can perform re-configuration after a robotic system is assembled with some kind of manual assistance. Manual configuring robots are in fact modular robots. They can only be re-configured with a sort of manual assistance. It is worth noting that parallel manipulators may belong to the last two categories. Furthermore, self or manual configuring can be used to overcome their main drawbacks. Because a parallel robot usually has a limited workspace, trajectory planning and application development can be difficult. In order to overcome the problem, the modularity concept can be introduced in the design of parallel robots.

Cable-based parallel manipulators are a class of parallel robots that consist of a fixed base (or frame) and mobile platform, which are connected by several cables. Therefore, they are structurally similar to the classical parallel ones, in which legs are replaced by cables. Due to the nature of cables (Irvine 1981; Kozak et al. 2006; Riehl et al. 2009), they possess in general favorable characteristics such as: good inertial properties, their actuator transmission systems can be fixed on the base, and cables are lighter and thus, they can have higher payload-to-weight ratio (Krut et al. 2008; Dekker et al. 2006; Albus et al. 1993; August design 2010). They can be relatively low-cost, modular, and easy to re-configure according to their design by relocating connecting points of cables (Castelli et al. 2009; Ottaviano et al. 2009).

In this Chapter an overview and issues are presented on the design problem for classical parallel and cable-based architectures, and task-oriented designs. A model for simulation and experimental set-up are presented for a novel re-configurable parallel cable-based robot, which appear to be interesting for application as motion assisting and aiding system.

2 Issues on Modular Re-Configurable Parallel Robots

Referring to parallel manipulators a re-configurable system consists of a set of modules, which may be identified as actuators, passive joints, rigid links (connectors), mobile platforms, and end-effectors, that can be rapidly assembled into a

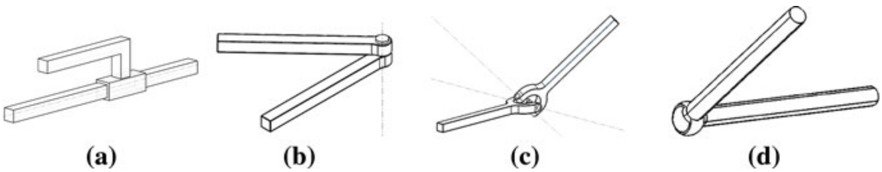


Fig. 1 Modules for parallel robots: **a** prismatic (P); **b** revolute (R); **c** universal (U); **d** spherical (S)

complete robot with various configurations. A modular parallel robot configuration thus can be rapidly constructed and its workspace can be modified by changing the leg attachment points, the joint types, and link lengths for a diversity of task requirements. Because of the re-configurability, a modular parallel robot system has unlimited configurations.

Most commonly used joints for modular re-configurable parallel robots are one DOF joints, such as revolute or prismatic pairs, two DOF joints, such as universal pairs, and three DOF joints, such as spherical pairs, as shown in Fig. 1.

It is worth noting that the above mentioned joints can be either structure or actuated modules.

Some authors classify structure modules for parallel manipulators such as passive joint modules (without actuators) (Yang et al. 2001).

It is also worth to mention that structure modules, which include end-effector modules, can be considered fixed-dimension modules. Rigid links, module connectors, and mobile platforms can be designed with customized dimensions. These modules usually have simple designs and can be rapidly built based on functional requirements. Allowing for dimensional change in module design provides the end-users the ability to rapidly fine-tune the kinematic and dynamic performances of the robot, especially, the size and geometry of the workspace. Therefore, a set of links and mobile platforms with various geometrical shapes and dimensions may be constructed as based on standard mechanical designs for saving costs.

For the sake of modularity, the actuated modules must be compact and therefore, they may be self-contained in intelligent mechatronic drive units. In particular, each drive unit may include a built-in motor (power module), a controller, an amplifier, and the communication interface. Communication and power transmission is provided by cables and suitable interfaces.

Selecting and combining the above-mentioned modules an unlimited number of parallel architectures can be obtained (Li et al. 2005a). Among all possible combinations non-redundant topological structures must be selected. A classification of configuration schemes for a class of parallel robots with 6 DOF is shown in Table 1, as based on the work of Podhorodeski and Pittens (1994).

The closed-loop structure of parallel robots imposes kinematic constraints on the dimensions of the robot sub-assembly, and makes the construction of a useful parallel robot configuration from entirely standard modules challenging.

Parallel manipulators commonly produced by machine-tool manufactures can be systematized in three main groups (Gogu 2007; Liu et al. 2007):

Table 1 Classification of non-redundant parallel robots with 6 DOF

No. of legs in parallel	1	2	3	4	5	6
No. actuated modules (1 DOF) in each leg	6	1,5 2,4 3,3	3,3,0 1,1,4 1,2,3 2,2,2	1,1,1,3 1,1,2,2	1,1,1,1,2	1,1,1,1,1,1

- Systems with variable leg lengths commonly known as Gough-Stewart platforms (i.e., Variax of Giddings & Lewis, Octahedral Hexapod of Ingersoll, Okuma Cosmo Center PM-600, CMW 380, DR-Mader Hexapod),
- Systems with fixed leg lengths and actuated by linear and/or rotating motors usually mounted on the fixed base (i.e., Delta-type Quickstep HS500 of Krauseco&Mauser, sprint Z3 of DS Technology, Urane SX of Comau, PA35 of Hitachi Seiki, Rotopod of Sandia, HexaM of Toyoda, Pegasus of Reichenbacher),
- Systems with a passive leg (i.e., Tricept of Neos Robotics AB, Tripteor of PCI, Tricept machining Center 845 of SMT Tricept AB).

In general, these parallel manipulators have coupled motions, moreover, the Gough- Stewart type platforms usually have 6 DOF, but for a large number of application, mainly in industrial environment, less than 6 DOF are needed to position (and orientate) the moving platform with the end-effector, which is usually a rotating tool (Herve 2006). Therefore, designing a modular re-configurable parallel manipulator may lead to consider a system with less DOF and use its capability of self or manual configuring to accomplish several types of tasks (Li et al. 2005b; Tanabe and Takeda 2010).

In the following an example of three-legged parallel robot is chosen as the norm of modular parallel robot design. In addition, the number of legs may affect the occurrence of leg interference. Therefore, considering a reduced number of legs can lead to less chance of leg interference. Leg symmetry is an advantage for parallel robots when uniform force distribution among the supporting legs and robot configuration control are considered. Furthermore, if in the design process unnecessary offsets of the leg links are eliminated and the joint directions are parallel or at right angle, the construction and kinematic modeling of the legs will be simplified and manual or self configuring will be greatly simplified.

Figure 2 shows an example of a re-configurable parallel manipulator with three legs. In particular, the actuated modules are the prismatic and revolute joints fixed on the base and the legs are composed by structure modules with fixed lengths. This manipulator allows manual configuring, since it may be possible to change the relative position and orientation of the actuated modules resulting in the configuration of Fig. 2a in which the prismatic pairs are arranged in parallel, and in the configuration shown in Fig. 2b in which the prismatic pairs are arranged along lines intersecting in one point. The above-mentioned configuration change allows obtaining different position workspaces, in terms of both shape and

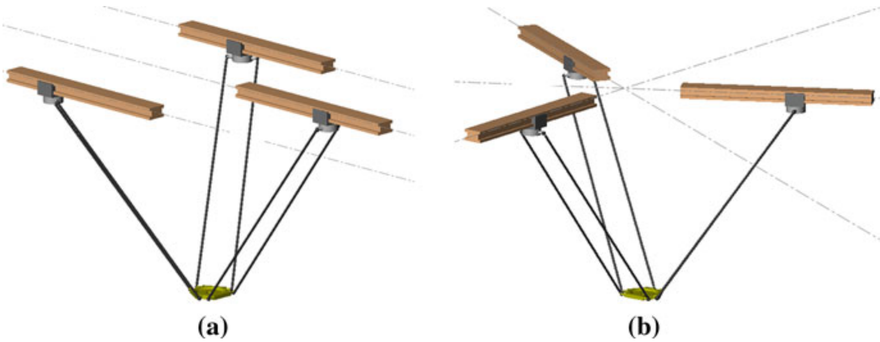


Fig. 2 An example of re-configurable parallel manipulator: **a** when prismatic pairs are arranged in parallel; **b** when they are arranged as intersecting lines

dimensions, as shown in Fig. 3. It is worth noting that the simulation result has been obtained by re-configuring the same basic modules.

The resulting position workspace in Fig. 3b is 2.4 times larger than the one shown in Fig. 3a in terms of volume.

The design methodology for re-configurable parallel manipulators is usually based on the sequential decomposition of mechanical, mechatronic and control subsystems, so that at each step a subset of design variables can be considered separately. Although this commonly used design approach seems to be intuitively practical, it does not take into account the high coupling among various subsystems that may indeed play a significant role in multidisciplinary systems (Lee and Sanderson 2001).

The need of correlation among subsystems implies that they must be considered together in the design and synthesis process. In an optimal design process, design requirements should be collected from all the disciplines, and they are offered equal opportunities to contribute to the current state of the design in parallel. The synergy resulting from integrating different disciplines in the design process has been used in a limited number of scientific works.

However, the challenge in a concurrent design process is that the multidisciplinary system model can become prohibitively complicated; hence computationally demanding with a large number of objective and constraint functions to be taken into account simultaneously with a great number of design variables.

Typically, the problem of robot configuration optimization can be formulated as finding a robot modules assembly that can achieve a certain task requirement. The assembly of a re-configurable robot can be treated as a compound entity with finite number of elements. Finding the most suitable task-oriented robot configuration then becomes a discrete design optimization problem. Issues related to the design of modular re-configurable parallel robots can be considered as: configuration selection, kinematic, singularity and workspace analysis. Because a modular robot may have unlimited assembly configurations, the selection of suitable module assembly configuration is important because it leads to a very different workspace and related features.

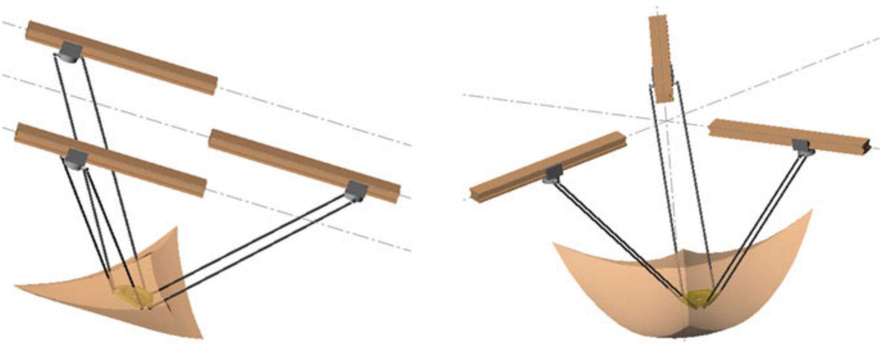


Fig. 3 Position workspace of the re-configurable parallel manipulator in Fig. 2: **a** actuated modules arranged in parallel; **b** actuated modules arranged as intersecting

Unlike conventional serial robots using Denavit-Hartenberg (D-H) parameters for kinematics models, general and systematic algorithms for the kinematic analysis of parallel robots are still an open issue in Robotics (Dasgupta and Mruthyunjaya 2000; Merlet 2006).

In the forward kinematics aspect, no general closed-form solution algorithm has been developed for parallel robots except for certain specific robot architectures. Furthermore, the derivation of forward and inverse kinematics becomes very complicated because their solutions may not be unique for certain configurations. Typically, the forward and inverse kinematics of parallel robots are derived based on a specific configuration and geometry (Bande et al. 2005).

Most of the closed-form solution algorithms make use of an algebraic analytical approach, and involve solving high order polynomial equations, which requires extensive computation effort (Angeles 2003; Merlet 2006). The kinematics of modular re-configurable robots can be formulated based on the Local Product-of-Exponentials presentation POE, which can uniformly describe the robot joint axes using generic line coordinates regardless of the type of the joints (Yang et al. 2001). It has been shown in related works that local POE formula is a systematic and well-structured method for the kinematic analysis of parallel robots.

Another key issue in the analysis of parallel manipulators regards singularity. Some authors studied a transformation for 6 DOF Gough-Stewart type platforms that preserves their singularities (Husty et al. 2002), thus it is possible classifying platforms in families sharing the same singularities (Alberich-Carramiñana et al. 2007; Borras et al. 2009). One such family of mechanisms has been studied in the context of composite serial in-parallel robots (Simaan and Shoham 2001). The outcome of this research is re-configuring parallel manipulators in such a way that singularity loci do not change. Furthermore, it is possible to characterize self-motions associated with non-trivial architectural singularities, which has an important practical applications in redundant parallel robots and re-configurable parallel robots. For example, a redundant parallel robot, in which its fixed platform attachments can be moved along guides, should be controlled in such a way that it remains far from this kind of singularities. Alternatively, another interesting application is in approaching them so that the robot stiffness is reduced in a given direction to ease some tasks requiring accommodation.

3 Issues on Re-Configurable Cable-Based Parallel Robots

Cable-based parallel robots are a class of parallel manipulators in which rigid links are replaced by cables, which may be exerted or retracted by suitable actuation system (Nist Robocrane 2010; Williams et al. 2004). As basic characteristic they may be modular and re-configurable, since main components are actuated modules (linear or rotary motors) pulleys, and cables, which must be attached by suitable connectors to the fixed frame and end-effector (or moving platform) (Ottaviano 2008a; Bruckmann et al. 2008). The simplicity of their mechanical design lead to cost savings and possibility to be deployable, portable, disassembled and assembled on site in the desired configuration. For cable-based robots either self or manual configuring can be considered. For instance, in manual configuring relocating of attachment points for cables can be performed either on the fixed or mobile platforms. Furthermore, a rebuilding to a complete new fixed structure using the existing components is possible too. After rebuilding, a new cable robot with new kinematic characteristics and a new workspace is available.

Self configuration deals with changing of kinematic characteristics in operation. This can include adaptive joints that can block one DOF or consider additional DOFs to move the connecting points in operation.

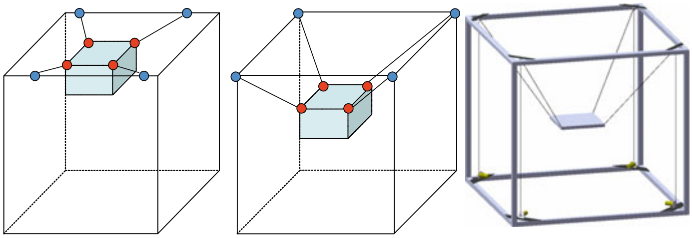
Figure 4 shows a scheme of possible configuration changes for a 4 cable and 7 cable-based parallel robots, in terms of a change of base and platform attachment points. In particular, the last schemes in Fig. 4a, b represent possible mechanical design including actuated modules (motors) and structure modules (pulleys).

It is worth noting that a self or manual configuring of the system will allow a different workspace. In Fig. 5 examples are reported for the position workspace of the two configurations of the 7 cable-based manipulator in Fig. 4b.

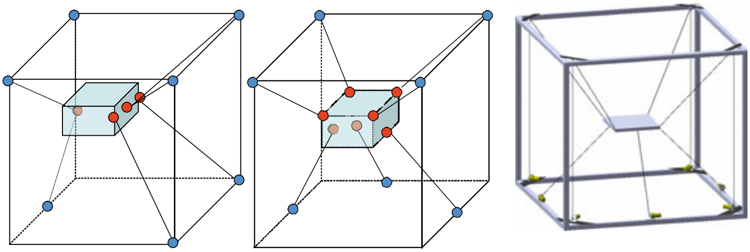
By changing three base attachment points and end-effector attachment points the resulting workspace volume changes more of 30%. Large differences can be found in the orientation workspace of the manipulator in the two configurations.

For cable-based parallel manipulators Kinetostatics or Dynamics should be solved in order to analyze the workspace (Kawamura et al. 2000). Unlike classical parallel robots for which the Kinematics can be rather difficult, a change of the configuration in cable-based robot does not increase the computational complexity of this analysis.

Issues for the design of modular re-configurable cable-based manipulators can be referred to the determination of the feasible workspace (Diao and Ma 2007; Gouttefarde and Gosselin 2004; Riechel and Ebert-Uphoff 2004; Roberts



(a)



(b)

Fig. 4 Scheme of possible configurations for cable-based parallel robots: **a** a 4 cable manipulator; **b** a 7 cable manipulator

et al. 1998), for which all the cables are in tension, and cables interference (Andrade-Cetto and Thomas 2008; Lahouar et al. 2009; Merlet 2004).

4 A Case of Study for a Re-Configurable Cable-Based Parallel Robot

The CALOWI (Cassino Wire Low-Cost Robot) is a cable-based parallel manipulator that has been designed and built at LARM, University of Cassino (Ottaviano 2008b). It possess 4 cables and thus 4 DOF, as well as a large workspace, if compared to the size of the fixed structure. The manipulator was designed initially for fully-constrained planar applications, and subsequently for spatial applications as under-constrained suspended robot. It has been tested for path-planning and rescue applications, for medical applications and to support mobility (Castelli 2010).

The prototype is shown in Fig. 6, in which the upper surface can be used for planar applications, and Fig. 6b shows the manipulator in the spatial version. The fixed structure is made of aluminum that is extremely light and yet has a good stiffness. This results in a reduced weight of the robot, which can be easily disassembled and assembled on site. The end-effector of the manipulator can have

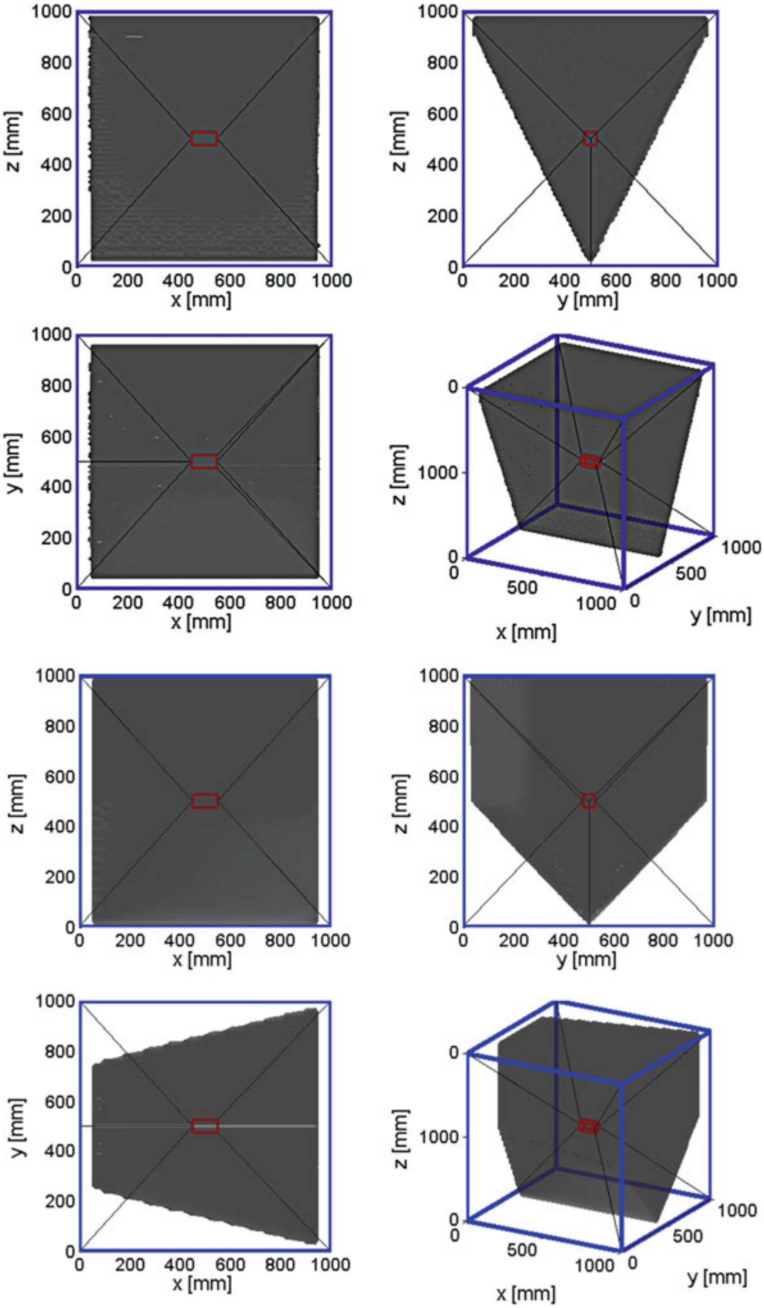


Fig. 5 Position workspace of the cable-based parallel manipulator in Fig. 4b

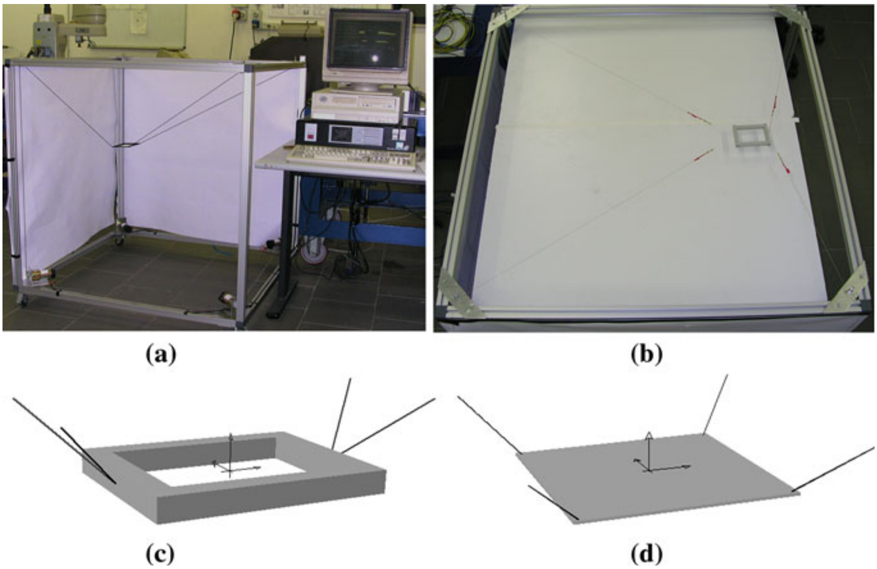


Fig. 6 The 4 cable-based manipulator CALOWI at LARM: **a** planar version; **b** spatial version; **c** 4-2 end-effector configuration; **d** 4-4 end-effector configuration

two different configurations: the first one has been named 4-2 with two attachment points and shown in Fig. 6c, and the latter one is named 4-4 with four attachment points, as shown in Fig. 6d. The system is equipped with load sensors to monitor cables' tensions.

The mechatronic design of the robot has been conceived by allowing the manual configuring of the system in one combination of the 4 possible cases that are shown in Fig. 6.

In the following it will be shown how it can be used as upper and/or lower limbs aiding motion system. The planar version is used for upper limbs and spatial version for lower limbs and as an assisting device.

Referring to the application of the system as upper limb motion assisting device a model of the cable-based manipulator was developed in ADAMS environment considering the planar version with the end-effector configuration 4–2, as shown in the scheme of Fig. 6c. For the purpose of under-investigation, an ad-hoc rigid body has been considered as end-effector. It is composed by a cylindrical element for the grasping action and a disc-shaped element to slide on a flat surface and allow some trajectories that can be set a priori. In Fig. 7a the overall model of the system is reported, consisting of the planar cable manipulator and human body model. The developed model in ADAMS environment can be complementary in a rehabilitation task for defining the objective and movements, through an appropriate simulation, and its numerical result can actively aid motions, in the process of rehabilitation itself (Mayhew et al. 2005; Surdilovic et al. 2007). Depending on the proposed tasks experimental tests were carried out by using the prototype

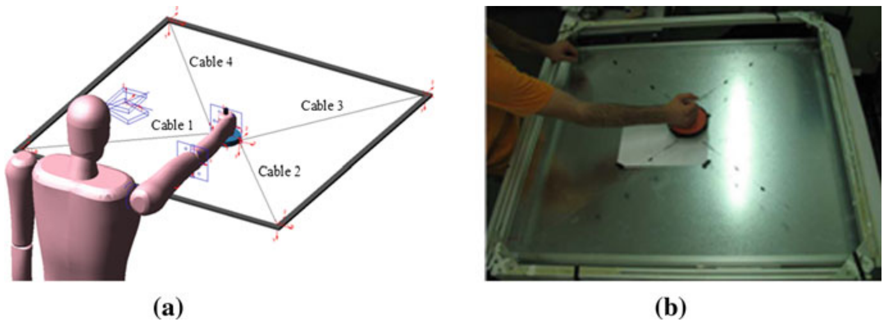


Fig. 7 A system for the motion aiding of upper limbs: **a** a model in ADAMS environment; **b** laboratory set-up

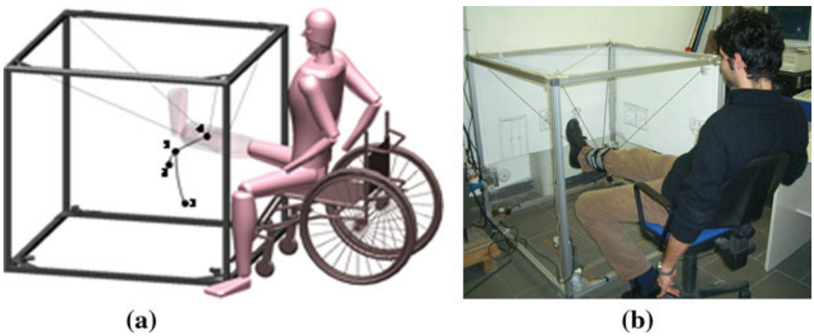


Fig. 8 A system for the lower limbs movements: **a** ADAMS model of the manipulator and human body; **b** laboratory set-up

CALOWI in the planar version and with end-effector configuration 4-2, according to the laboratory lay-out shown in Fig. 7b.

The same 4-cable based manipulator has been used as assisting motion system for the thigh and leg. The model of the human body in Fig. 8a is seated on a wheelchair, which is considered attached to the fixed frame of the manipulator and moving parts are those inherent to the right lower limb: thigh, leg and right foot.

Figure 8a shows the model of the CALOWI manipulator that interacts with the human body, simulating the aiding motion application.

In particular, first experiments were carried out considering the manipulator in the spatial version with the end-effector configuration 4-4 for laboratory experiments involving adult healthy volunteers. The lay-out for the experimental tests is shown in Fig. 8b).

It has been experimentally verified that manual configuring for a cable-based manipulator is an easy and fast task. Furthermore, the mechanical design of the fixed frame and pulleys were developed by considering the possibility of self configuring of the robot by adding actuating modules to the system.

5 Conclusion

In this Chapter issues related to the design of modular re-configurable parallel robots have been reported, referring both to classical parallel structures and cable-based manipulators. In particular, examples of workspace variation are reported for both classes. The design of a modular re-configurable parallel manipulator is still an open issue in the Robotics community since it is a multidisciplinary and complex process. Issues to be taken into account are addressed for manual and self configuring, both for classical and cable-based manipulators. A case of study of a modular re-configurable cable-based robot is proposed as assisting and aiding motion system.

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Human Centered Mechatronics

Alberto Jardón Huete and Santiago Martinez de la Casa

Abstract Mechatronics is an applied interdisciplinary science that aims to integrate mechanical elements, electronics and parts of biological organisms. Mechatronics' end goal is to design useful products. When those products are focused in human welling, helping them or by restoring lost capabilities, any mechatronics solution should consider at the beginning of the design process that all the mechanics, control and electronics must work cooperatively with and for human. Several challenges related to control issues and the role of human and machine in the control loop could be better achieved if human centered mechanical design approaches are assumed. From a mechanical point of view the development of robots that could operate in close interaction with human is a big challenge. Soft human–robot interaction is the branch that covers those topics. To analyze this fact, in this chapter, a general classification of the different types of robotic systems that currently could be found as well as actuators commonly used. The safety of the robotic assistant, working in close cooperation with humans, is currently a topic of interest in the robotics community. There are many ways to design and conduct intrinsically safe systems, from those that use complex sensory systems to monitor the user within the working environment to avoid contact, even the most sophisticated seeking to minimize the inertia of its moving parts (links) in order to reduce damage in case of accidental collision. Safety mechanisms will be reviewed based on variable stiffness actuators, novel designs of all-gear-motor shaft, etc. The study will include risk assessment and safety for the user. Risk and safety standards will be reviewed. Taking into account undesired collision, two types of safety strategies are reported: pre-contact and post-contact strategies. The first minimize the possible effect of the accident before it occurs. The latter should

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N. E. Nava Rodriguez (ed.), *Advanced Mechanics in Robotic Systems*,
DOI: 10.1007/978-0-85729-588-0_5,

minimize the consequences of that accident. Those new advances in the design techniques are being applied for ultra-light weight robotics arms and also prosthesis combined with new solutions in kinematic synthesis, materials, geometry and shape of mechanical components, actuators technologies and new thermal and FEM analysis techniques to validate them.

1 Introduction

Service robots can be used in a wide range of applications. Many technical problems derivate from this fact because they require a high flexibility when being handled, showing a great adaptability, however. They must work in environment which has been adapted according to humans' needs. There has been an increasing demand for their application in task where humans are present or/and where it is required a physical interaction between humans and robots. It is in those situations when the interaction problem appears. Interaction between robot and humans should be performed in a safe way. Robots shall guarantee safe behavior when human contact occurs. This requirement has been denominated "Human-friendly robots" by some authors. However attaining established levels of performance while ensuring safety creates formidable challenges in mechanical design, actuation, sensing and control. To promote safety without compromising performance, a human-friendly robotic technique must become human centered. These techniques and devices make use of cooperative tasks between robots and humans for performing many useful activities while guaranteeing the safety.

When service robots have a direct contact with humans and they interact with them, they are denominated assistant robots. According to Helms et al. (2002), an assistant robot is that adaptable device which interacts directly for providing assistance, using sensors, performers and processing. These assistive robots' evolution gave pass to the personal robots whose work is to carry out a wide range of tasks. This means a modification in the device's "personalized use". Perhaps there is not any other more joined application as the adaptation of prosthesis for a specific user (here the interaction is constant). The development of prosthesis has been tightly linked to the development of assistant robotics. This application demands nowadays several mechanic and Soft pHRI control solutions. Although the story of these devices started 30 years ago, its evolution has not been the expected one. There are several reasons that justify this stagnation. Firstly, the little functionality obtained regarding the use of healthy arms and hands, due not only to mechanical limitations or control strategies but also, to the user's possibilities when transmitting the proper orders to produce the expected movements. A way to perform this is to use the own user's mioelectrics signals (those produced by the brain when moving body muscles). It is very complicated to define the proper simultaneous control strategies for the position and stiffness of each joint, in such a way that it will be possible to obtain a similar performance to that of a healthy extremity (Del Ama et al. 2010). Finally, we have to mention the need of several sources of power to feed the engines; therefore, in order to obtain a certain autonomy, the user ought to carry those power cells around the performance area. All of these things have come up during the search of a compromise among accuracy, aesthetics and operative conditions. The goal is to develop solutions based on prosthesis with specific functions but they should keep a minimal aesthetics and operative conditions. These problems appear in other applications, as we will see further on. Recently researches are those of Rahman et al. (2006) in the AI duPont Institute (US), who designs passive upper extremity prosthesis as easily adjustable link lengths and anti-gravity lift. While the previous one is a counterweight system that does not require external power, the Mulos project (Yardley et al. 1997) is electric upper extremity prosthesis. Some of these developments are the Utah arm and hand prosthesis developed by Jacobsen et al. (2008) in the MIT or the one carried out by Kyberd et al. (2001) of a prosthetic hand in Southampton. Those works have progressed when including "Soft-robotics" techniques that will be described later on. An example is the development of prosthesis in an upper body exoskeleton to provide power to the arm and a lower body exoskeleton. This fact benefits the user thanks to the augmentation to the legs during walking activities through the use of pneumatics muscles (Caldwell et al. 2007).

2 Safety Strategies for Close Human–Robot Interaction

As practical robots operate in a dynamic environment, unexpected collisions between the robot and the environment are likely to occur. It is important that during these collisions, both the robot and the object it is colliding with suffer as little damage as possible. This becomes even more important when the robot operates in an environment together with humans where impacts can cause serious consequences. Assistive robots needs more than others to operate close and also in contact with humans, so their design must follow different requirements than those of conventional industrial applications: safety is first and foremost. An inherently safe system is a clever designed mechanical arrangement that cannot be made to cause harm. Obviously the best arrangement could be achieved but malicious use is always possible. We are interested in fail-safe systems which cannot cause harm when it fails. It should be developed in those technologies that allow a close interaction with the user. If the future designed robot needs to perform movements close to the user or, in some circumstances, to have a direct contact with him the main goal will be to guarantee safety every time. The robot must work in a harmless way, working in an usual way, not even in case of grave failure. After making sure of this, we can set out objectives regarding the robot's performance, functionality, speed and accuracy.

3 Risk Assessment and User Injury

Robots meant for physical Human–Robot Interaction must remain safe against all possible circumstances, including unexpected impacts. The risk is the resultant measure of multiplying the foreseen consequences after a failure by the probability for this to happen. When analyzing this risk in robots, we distinguish four levels according to the risk degree, (Bell and Reinert 1990; Corke 1999): and the probabilities for the robot harming the user: without enough strength, harmless, serious harm and death. Industrial robots are usually classified between the levels 3 and 4, however, the risk degree can be reduced by avoiding people to get into the performance area. If someone trespass the safety area, the robot will stop. There is only one program mode for allowing people inside the performance area and it is when robot's speed is limited. It is necessary to provide mechanisms which keep user' welfare all the time. The biggest risk in RA lays on a possible robot arm's collision when performing handling tasks near the user. Some authors classify the safety strategies as pre-contact strategies and post-contact strategies. The first ones have to minimize the possible effect of the accident before it happens. The second ones have to minimize the effect of the accident. Regarding the automobile industry, the ABS will be regarded as a pre-contact mechanism; the design of structures for absorbing the impact energy will be regarded as post-contact mechanism. From a designer's point of view, it is quite interesting to distinguish between mechanisms that should be considered from the initial design phase and those that will be used during the robot's performance. Recently, many efforts have been carried out for including safety protocols from the beginning of the design phase. Some authors (Ikuta et al. 2003) have been focused on quantifying the damage suffered by the users only when the implemented strategies have failed. The final goal is to design robotic arms which, in case of an accident, inflict the least possible damage. The level of the provoked harm through a collision is a well documented topic in biomechanics with the peculiarity of being focused on the automobile and sport world. Several index for measuring the gravity of the injuries have been written, among them we can point out the Gadd Severity Index (GSI), the Head Injury Criterion (HIC), the criteria "3 ms", or the Thoracic Trauma Index (TTI), the Viscous Injury Response(CV), or Thoracic Trauma Index (TTI). Many of them make reference to restriction curve of tolerance developed by the Wayne State University (WSUTL) which are based on the experimentation over animal corpses in 1,960. Those experimentations show the acceptable acceleration regarding the impact time being the damage criteria that of the cranial fracture in corpses subjected to an impact against plain and hard surfaces. This WSUTL curve put in relation the acceleration caused in the corpse's head versus the impact span, shows that it is possible to apply very high accelerations if they have a short span, however, those acceleration whose span is under 10 or 15 ms are less tolerated. Recently, many similar researches have been carried out on the robotic field (Zinn et al. 2002). A frequent expression obtained when evaluating the harm produced is the Gadd's equation which is obtained as a consequence of the WSUTL, called Gadd Severity Index expressed as followed:

$$\mathrm{GSI} = \int_0^T a^n d\tau, \tag{5.1}$$

where a is the head acceleration, n (frequently 2.5) is a weighty factor and T the pulse span. If the value of this index is over 1,000, the acceleration pulse is considered dangerous for life. Versace (1971) establishes that, due to the WSUTL drawn by the average acceleration; any comparison should be performed taking into account the average acceleration of the pulse of interest. Thanks to this aspect and the Gadd's expression, the Head Injury Criteria (HIC) can be described as followed:

$$\mathrm{HIC} = T\left[\frac{1}{T}\int_0^T \mathrm{a}(\tau)d\tau\right]^{2.5} \tag{5.2}$$

T corresponds to the final impact time. Due to the difficulty when calculating this time span it is necessary to consider the worst HIC value with a variable T where T is similar to the time spent by the head reaching its highest speed (usually, $T \leq 15$ ms). A HIC value similar or higher to 1,000 is typically associated to a very critical head injury; a value of 100 is the appropriate one for a proper performance of a machine physically interacting with humans. A HIC generalization allows us to consider collisions in other body areas. We only need to substitute the coefficient 2,5 by other value empirically defined (Zinn et al. 2002). In order to obtain a more basic and useful equation for a optimizing design process, we need to consider the basic case of a stiff arm in a robot with freedom of movements, moving at a V uniform speed before impacting against a human. The integration of movement equations, according to the HIC equation, allows presenting a safety index for Robots through the expression:

$$\mathrm{SIR} = 2\left(\frac{2}{\pi}\right)^{\frac{3}{2}}\left(\frac{K_{\mathrm{cov}}}{M_{\mathrm{oper}}}\right)^{\frac{3}{4}}\left(\frac{M_{\mathrm{rob}}}{M_{\mathrm{rob}} - M_{\mathrm{oper}}}\right)^{\frac{7}{4}} v^{\frac{5}{2}} \tag{5.3}$$

M_{rob} is the effective total mass of the robot, M_{oper} is the mass of the impacted operator and K_{cov} is the global stiffness of the robot's arm presenting a protecting cover. The SIR index, and generally the HCI in a robotic context, has been investigated with very satisfying results (Echávarri et al. 2007). Through obtaining risk coefficients, during the robot's design period, it is possible to evaluate quantitatively the effect when introducing a specific mechanism, for example, introducing chamfers into the link structure to minimize the injury risk in case of accident, covering the area absorbing the impact, or applying any variable impedance control system. Following the electric analogy we can define the mechanic impedance as:

$$\mathrm{Z}(s) = \frac{F(s)}{V(s)} \tag{5.4}$$

V(s) is the body speed and F(s) is the strength to which the contact point is being subjected (Homayoun and Bon 1999; Heinzmann and Zelinsky 1999). These advanced impedance control techniques (Hogan 1985) allow carrying out many advance handling tasks, controlling in a precise way the forces applied in the edge. They require complex dynamic robotic models and strength sensor on the wrist. Although these control systems are very sensitive to the changes and errors in model parameters, recent researches are analyzing the solidity of the active impedance control schemes for detecting collisions. Specially, it is very interesting to see the effect of the post-collision strategies facing collisions on different body parts (De Luca et al. 2006). As an attempt to define some standards and benchmarking, the crash-tests of light-weight robots has been systematically investigated. Standards and guidelines for the evaluation and comparison of safety in physical human–robot interaction are basically still an open issue and were up to now only addressed in ISO 10218 form the standardization body's side. In (Haddadin et al. 2008a, b) a first proposal for a set of standardized robot-dummy crash-tests is presented. ISO is developing standards for safety and the vocabulary for service robots and considering other aspects such as performance and characteristics of the robots of the future (Virk et al. 2008). IEC has recently initiated the standardization of the methods for measuring the performance of household cleaning robots (Rhim et al. 2007). This is a hot issue in human centre robotics and SO TC 184/SC 2, is a work committee which has been active in developing standards for industrial robots and has widened its scope recently to include service robots as well as industrial robots (Virk et al. 2008). In the following section a review of strategies and mechanism for reducing risk are presented.

4 Risk Reduction Mechanisms

The traditional approach for robot design includes a motor and a gear making a rigid, heavy robot to behave gently and safely in an almost hopeless task if realistic conditions are taken into account. In order to try to achieve less risk, active control strategies were adopted as mentioned above. Modifying controllers for rigid robot manipulators to achieve stiffness, impedance control needs add sensors (force, contact and proximity) and complex low level control schemes. There are intrinsic limitations to alter by control the behaviour of the arm if the mechanical bandwidth is not matched to the task. So a co-design of mechanics and control is unavoidable. Among the strategies mentioned in the literature (Dombre et al. 2001), can be found various mechanisms, which must be taken into account from the design phase itself (Bicchi et al. 2001; McDermid 1990). As an example, the relative location of the robot to the user during the execution of a path, dramatically affect the safety. A sudden shoulder side change needed to avoid a singularity, can hit the user. From the very conception kinematics in the design phase: from the size and range of each link to the choice of DOF (Jardón 2006) to the use of "damper" or touch sensors. Initially, it was proposed to gradually increase the number of sensors to avoid collisions. This mechanism led to the extreme, has led to the use of proximity–sensitive skins, as proposed by Cheing and Lumelsky (1989) and Iwata et al. (2001). Following the traditional approach of stiff actuator, others authors have been employed soft structures and elastic materials. Then the first was to minimize rotor and link inertia, use inertia compliant covering if possible. The addiction of soft covers in the links surfaces to limit the transmitted inertia in case of collision. The avoidance of sharp or cutting shapes, effectively decreased risk, but must be accompanied of a speed reduction to decrease injury potential. One of the earliest works in the area is e.g., TOU flexible manipulator Casals et al. (1993) developed at the Technical University of Catalonia. Other way to decrease the inertia is the introduction of elastic elements in the output shaft, a series elastic actuation (Pratt and Williamson 1995). The disadvantage of elastic coupling is clearly a degradation of the performance. Intuitively, the elastic transmission makes the link to respond slowly to an input torque and oscillations occur around the target position, so it is expected that the response time of an elastically actuated arm increases dramatically. The problem of controlling passive elastic joint to recover performance has been extensively studied in the robotics literature, both in the general case (Spong 1987; De Luca and Lucibello 1998; Kelly et al. 1994; Lanari et al. 1993) and in the context of safety-oriented design (Pratt and Williamson 1995).

Other systems make use of reversible geared motors and mechanical limiters through calibrated clutches that do not overpass a specific torque, in such a way that the motor continues turning but the produced movement is not transmitted to the exit axis. These mechanisms minimize the risk of getting trapped by the manipulator. This fact requires either limiting the power of the performers in the design (optimizing its size to the task requirement avoiding the over sizing) or through executing control with a software working on the supervision of the power consume, or through the use of specific sensors to limit the torque in each motor axis. The generation of DLR light-weight robots is among the most advanced implementations of the “traditional” approach implementing active control schemes impedance (Hirzinger et al. 2003). It aims to control the position and strength by adjusting the mechanical impedance in each axis and therefore at the end of the robot. The control adjusts the stiffness of the arm as the external forces that are generated when contact with the environment or the user (Hogan 1985; Heinzmann and Zelinsky 1999). In any case, anti-impact implement strategies, which means being able to distinguish between contact and collision (Homayoun and Bon 1999), which is not a trivial problem in robotics-friendly being application-dependent. This approach also meets the following restrictions: 1. Limited torque/link inertia ratio, 2. Limited mechanical bandwidth, 3. Limited sample bandwidth. The fact is also the most advanced lightweight manipulators show a not depreciable delay for collision detection. Consequently some authors conclude that active force control is unsafe in real conditions and propose actuators based on variable stiffness actuators (VSA) (Bicchi et al. 2003), allowing the dynamic decoupling of the actuator link, but always moving reducing inertia.

5 Light-weight Robots: The Role of the Inertia and the Compliance

The main idea is to keep low weight mass in movement to secure low risk of injury in case of accidental collision, as its reduces the kinetic energy. The use of lightweight manipulators, to minimize the risk, is a strategy widely accepted as having less mass in motion the consequences of stroke if it occurs will be lower. An example of the interest that is causing the safety is reflected in the number of ultralight manipulators that has been developed in the German Institute DLR. These prototypes are characterized by low inertia of its links to have reversible actuators and complex impedance control system based on force-torque sensors built into each axis (Hirzinger et al. 2003). For the development of ultralight robots it is critical to set the items on board to a minimum in size and number, to achieve the minimum total weight of the prototype. To achieve this integration requires: embed all the elements of board control and appropriate selection of structural materials, concurrently completing the mechanical and electronic design, minimizing the size and weight of all control elements, all of this while satisfying the needs of the application (Jardón 2006). This weight reduction is limited in practice by the payload specifications, motor power adjustment and material selection for link structures. Payload is normally related to the task. As assistive arm must be at least strong as human ones, but too much power will increase unnecessary the weight of the arm making it less potentially safe. Also the design factors as size or the length plays an important role in the end design. The most advanced lightweight manipulators has got payload/weight ratios of near 1, (as DLR III without control cabinet) and typically 0.15–0.35. If one person could move/hold the robot, shapes and volumes are also important. Clamping risk must be avoided if design assures portability. Aspects of system reliability and safety are particularly important in applications where the stake user's physical integrity, especially when it has reduced its physical and (or) mental abilities. Bear in mind that full accuracy and safety of the system is not feasible, (Harwin and Rahman 1992; Van Der Loos et al. 1992), so it is necessary to know the maximum acceptable ratio of cost/risk according to the expected benefit. This leads to the design of such systems which should include mechanisms for the user to lose control of the system, even in the event of failure of any of the systems. Lately the research efforts try to deep in the holistic concept of dependability: A system is dependable if it is able to deliver the service (function) as expected, for the time that it is necessary (i.e., reliable) or at the instants when it is demanded (i.e., available). A system is safe if the interruption of the service does not lead to catastrophic consequences or its likelihood is negligible.

6 Design for Safety-Performance Trade-off

In human–robot interaction, accurate positioning is secondary against the "natural" soft interaction. Also in assistive devices the time to perform a task is not so critical, so slow motions are welcome. That is, certain safety strategies involve a reduction in benefits for the robot. For example, the speed limit is a wrong in the execution of any task to increase the time it takes to complete. Bust most of our daily activities involve interaction with the environment, so improving these abilities is an important area for design. The trade-off between safety and performance is the key issue for PhRI, the last year trend is changing from stiff non-heavy robots, highly sensitized and powered with complex compliance controllers, towards friendly and soft robots. Simultaneous control of motion and stiffness can be achieved by explicit stiffness control. The optimal balance between safe behaviour and required performance is still an open problem. For solutions that involve an optimal balance between both factors, some authors propose actuators based on transmissions of variable stiffness VSA (Bicchi and Tonietti 2004), but the best solution will obviously depend in each case to consider. Examples can be found taking advantage of the incorporation of sensors of the robot itself, to be used also as an interface. In this line emphasizes the MOBMAN robot, developed within the project Morpha (Project MORPHA 2001), consisting of a mobile base equipped with manipulator, with 13 total DOF, has got in all its housing a kind of "artificial skin" provided with force sensors. Force sensors are used to measure the user' forces when he leads the arm in the desired positions by allowing guided programming by touch interaction (Wichert and Lawitzky 2001).This also allows the touch sensor to be used by the user to steer the robot when it is in an ambiguous situation and cannot go out by itself. The Barret WAM (Whole Arm Manipulator) is a tendon driven light weight which could be considered the first intrinsically safer pHRI robot. Developed originally at MIT and sold by Barrett Technology Inc, (Brooks 1991) a high dexterous three-finger hand is integrated. As presented previously the generation of DLR light-weight robots is among the most advanced implementations of the "Safely controlled" approach in order to achieve intrinsically safer robots (De Luca et al. 2006). Also a highly complex hand design is integrated on the tip. Based on the DLR LWR-III, industrial robotics manufacturer KUKA sold it as a research platform. The KUKA light-weight robot is similar to the human arm with seven degrees of freedom. Each joint has sensors for joint position and joint torque. The KUKA robot controller can operate the robot in position, velocity and torque-controlled. The first example tends to achieve safety interaction by means of low inertia links design and mechanically "back-drivability". The second one by means of light weight and active controls based on the intrinsic sensing of forces, that allows changing arm behaviour from soft and compliance to highly rigid if needed. Some previous work was based on air muscles, (Daerden and Lefeber 2002; Verrelst et al. 2006), DEXTER cable-actuated robot arm from ARTS Lab of Univ. SSSA Pisa. Also the presence of flexible and compliance elements has been demonstrated useful, as the flexible and soft covered arm TOU (Casals et al. 1993).

The following section approaches try to keep low levels of injury risk changing continuously during task execution the value of mechanical variables such as stiffness, damping, and gear-ratio. The stiffness can be adjusted mechanically as or the Mechanical Impedance Adjuster (Morita and Sugano 1996), by means of a mechanical/control co-design that implies an extra motor to change it dynamically, like variable stiffness actuator of (Bicchi et al. 2003). Some prototypes that meets this approach are the Wheelchair-Mounted Robotic Arm of Sugano Laboratory in Waseda University, and the arms of TWENDY-ONE assistive mobile platform (Twendy 2010).

7 Practical Approaches for a Designer Perspective (some Successful Cases)

The passive approach to implement variable stiffness pretends to guarantee the safety level by means of the optimization of the actuator's mechanical structure. A set of two or more linear actuators in an antagonistic configuration about the joint are used or, by means of non-linear spring as an elastic transmission between each of the motors and the actuated link. This mimics the arrangement of antagonistic muscle pairs acting about a joint. By using physical springs driven by nonbackdrivable actuators, constant forces can be applied without the constant input of energy required in the active case. The big advantage is that they are highly energy efficient; they only need to overcome friction losses.

8 Equilibrium-Controlled Stiffness

These compliant actuators use a fixed stiffness spring in series with a traditional method of actuation. The measurement of the unit displacement and force on the spring is applied to adjust the torque supplied by the motor, otherwise known as impedance control. To obtain variable stiffness, the virtual stiffness of the actuator is adjusted by dynamically adjusting the equilibrium position of the spring (Van Ham et al. 2007).

Sugar has also developed a spring-based actuator (Bharadwaj et al. 2005), which uses the concept of equilibrium-controlled stiffness. A linear spring is added in series to a stiff actuator, and the equilibrium position of the spring is controlled to exert a desired force or desired stiffness (De Luca and Lucibello 1998; Thorson et al. 2007). The compliance is actively changed using a control law instead of fixing the compliance by passively adding springs. The force-control problem is converted to a position-control problem using electric motors. The motor position is adjusted based on the deflection of the spring to alter the tension or compression of the spring.

9 Antagonistic Controlled Stiffness

This way of stiffness control is based on the same principle used in the human elbow joint. Biceps and triceps are antagonistic actuators, that is, they produce movement in opposite directions. This kind of actuators can only move in one direction. Then the joint needs at least two actuators to be moved in two directions. In this case, the joint resulting stiffness depends on the value of the antagonistic forces applied by the actuators. Migliore et al. (2005) describe a device based on an antagonistic combination of two non-linear springs. The mechanism consists of two rotary servo actuator joined by two linear springs. The joint equilibrium position changes when the servomotors rotate in the same direction. If the servomotors rotate in opposite directions the joint stiffness is adjusted. The main advantage of this design is the selection of force–elongation characteristic of the springs during the design stage. The disadvantage is the size of the device, complexity and friction of mechanisms. Other antagonistic systems based on the same principles are described deeply in Koganezawa et al. (2006), English and Russell (1999), Tonietti et al. (2005) and Hurst et al. (2004). An alternative to linear springs for the stiffness modification are the pneumatic artificial muscles (PAM). These devices use the compressibility property of the air inside an elastic material chamber. In this way, the muscle has similar behavior than springs. McKibben (Chou and Hannaford 1996) muscle is the most popular. The problems of these kinds of joints are their non-linearity, slow dynamics, hysteresis and the necessity of compressed air. The pleated PAM (PPAM) (Sulzer and Peshkin M Patton 2005) solves some of the mentioned problems.

10 Structure Controlled Stiffness

The modification of the elastic element structure is an alternative to the configuration of antagonistic linear springs. It is called SCS (Structure Control Stiffness) (Bharadwaj et al. 2005). For instance, the inertia or the length can be modified in these mechanisms. Kawamura et al. (2002) suggest a structure composed by thin glass sheets inside an elastic plastic chamber. The applied normal force folds the device but, if vacuum is applied, the sheets are compressed and the stiffness of the device is increased. This system is very easy to build but the friction between sheets is difficult to control. Recently, a new type of actuator, based on the concept of length variation, was presented in (Hollander et al. 2005) and called as Jack spring. Mechanic adjustment can be made changing the number of active coils.

11 Mechanically Controlled Stiffness

Other alternative is the design of actuators based on mechanically controlled stiffness. Derived from the concept developed in the Vrije University in Brussels, the MACCEPA (Van Ham et al. 2007) device consists of three bodies rotating around an axis. One spring is placed between point c and b. Its stiffness is controlled mechanically by a servomotor. The joint angle φ is established by another servomotor. The main advantages of MACCEPA device are the linearity of angle-torque characteristic and the independence between stiffness and position control. Even though, joint friction depends on its stiffness and the servomotors need more space inside the structure. By other side, the German Aerospace Centre (DLR) proposes other type of device: the variable joint stiffness (VS-Joint), as presented in (Haddadin et al. 2008a, b). The main idea of this device is the length variation of several springs and, consequently, its stiffness. The preset stiffness is controlled by a little servomotor. During operation, the joint motor produces its rotation and a cam mechanism adjusts dynamically the output stiffness. This joint allows an easy stiffness adaptation depending on the application. In the particular case of ASIBOT assistive robot, due to its space and weight limitations, two main goals have been adopted in the design process from a mechanical point of view: the first is to decrease the overall weight meanwhile new sensors and subsystem may be introduced on board. The second try to find better actuators, is to increase payload to weight ratio, but improving safety. The idea is to uncouple motor inertia of the actuator output shaft by means of a VSA inspired magneto-rheological fluid clutch, called MRJ (Casillas et al. 2007). The working principle of this novelty design MRJV1.0 is found in its blade. This shape is designed to achieve variable friction depending on the magnetic field generated. Controlling the field, friction can be controlled. Due to the friction characteristics of the fluidized blade, the coupling between input and output shaft changes. Although some work is required to validate the solution proposed in order to test the efforts in working phase, some FEM analysis support this line. A schema of the first results is presented at (Casillas et al. 2007). Some real prototypes are still under improvement in order to validate the technical viability for the adoption of this technology for new ASIBOT generations of actuators, but due social motivation an economical study must be passed. The light-weight robot ASIBOT2, aims to be a domestic robot assistant without on board intelligence, but safe and reliable with its mechatronic design and force-torque sensing, cameras at the tips, and control along the entire robot structure. Our target is to develop and test new light-weight domestic climbing robot specifically designed and programmed for human–robot interaction in domestic environments, "dependability proved". Extensive experimental and clinical trials and direct user implications on design stages are needed to find a widely accepted solution.

12 Conclusion

This is a review about some requirements, technologies and methods to be included in the design of practical friendly or human oriented robots. Related to the most promising actuators developments some considerations must be adopted. It is critical to develop collision detection schemes with high sensitivity for injury prevention for both joint classes presented above: active compliance and passive compliance (VSA joints based). Clear advantages for the last approach has been reported (Haddadin et al. 2010) in joint protection during impacts with the environment and the large performance increases that are achievable. As the main goals of running VIACTOR[1] VII EU projects claims “developing and exploiting actuation technologies for a new generation of robots that can co-exist and cooperate with people and get much closer to the human manipulation and locomotion performance than today’s robots do. At the same time these robots are expected to be safe, in the sense that interacting with them should not constitute a higher injury risk to humans than the interaction with another cautious human”. “This ambitious goal can, however, not be achieved with the existing robot technology”. Focus on human-friendly, variable stiffness actuators are a proven mechanism to provide intrinsically compliant behaviour. The suggested line of research is to embed on robots methodologies to supervise energy storage of its elastic elements. Those components could generate unsafe high speeds, when the controller is trying to suppress unwanted tip oscillations. These methodologies must cover from collision avoidance, detection and reaction strategies working according to cognitive related high level fault modules that evaluate and supervise system awareness of the user oriented task.

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Mechanical Design Thinking of Control Architecture

Nestor Eduardo Nava Rodríguez

Abstract Modern research prevents interdisciplinary activities, in which experts of several fields work together in order to obtain a final solution with high performance characteristics. The main fields in robotics are control, electronics and mechanics. These areas are highly close and they must collaborate together in robotic projects deciding the most suitable solution of every sub-system for a successful operation as an integrate system. For example, a suitable mechanical design can simplify the requirements of control and electronics. This chapter deals with the importance of the mechanical design in the development of mechatronic devices as easy-operation systems. Low-cost robots are related to new emerging application areas and they can be also operated in a simpler way compared to the typical industrial robots. The synthesis process of mechanism that composed the robotic structures represents a key phase in the mechanical design of easy-operation prototypes. The main idea is to obtain dynamic systems in which their transfer functions do not present undesirable characteristics from the control point of view, for instance, all poles equal to zero or non linearity of inputs. For this goal, the mechanical designer should consider the recommendation from the control strategist during the mechanism synthesis. Similar, backlash, hysteresis, shafts offset and fiction are also undesirable mechanical characteristics for non complex control architecture. Some tips are reported in this chapter for a mechanical design in which these undesirable characteristics are reduced as much as possible.

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N. E. Nava Rodríguez (ed.), *Advanced Mechanics in Robotic Systems*,
DOI: 10.1007/978-0-85729-588-0_6,

1 Introduction

Several powerful strategies have been developed in order to revolve the problem of controlling complex engineering systems. Hysteresis, backlash, friction and vibration are typical problems found in mechanical structures that yield unsuitable responses (Ogata 1998). Successful method of linearization have been developed and included as part of strategies that compensate these kinds of phenomenon. The modern control engineering includes using strategies, for example neuronal networks, evolution strategies, artificial intelligence even cognitive science, to build strong architectures with the capacity of compensating complex dynamic systems. These control systems contain complex codes that require high computational efforts and modern hardware resources unfeasible for robotics applications. Autonomy is one of the most desired characteristics for a robot prototype, thus the control system should provide the possibility of fulfilling this requirement in term of low-weight, compactness and suitable dimensions. In the main cases, hardware with these characteristics presents high cost and needs personnel with high technical knowledge. Therefore, not so-complex control architecture is always considered a better solution for a practical application of a robotic system. The design of a mechanical structure with characteristics that do not require high compensation due to non linearity problems can reduce the complexity in the design of a control strategy. Moreover, an adequate synthesis of robot mechanism, in order to make it as compact as possible, can generate kinematics and dynamics formulations that allow controlling by implementing traditional control systems. For example, a mechanism with a kinematic chain with only revolute joints presents simpler kinematics and dynamics than a mechanism with spherical, prismatic and cylindrical joints. Similarly, a reduced number of DOF (degrees of freedom) helps to reduce formulation.

I present in this chapter some guidelines for the design of robotics system with easy-operation features. Considering these guidelines, the result solutions of the design process present robustness, compactness and accuracy. Some representative examples of systems designs considering the proposed procedure have been illustrated. Not so-complex control architecture can be applied to manage these robots.

2 Guidelines for an Accurate Mechanical Design Through Illustrative Examples

In the mechanical design, some details must be always taken into account in order to avoid problem for a correct operation. Moreover, if a machine performance is accurate it will be controlled in a not so-complex way. Now, some tips in the mechanical design are going to point out for cancelling mechanical phenomenon that can make difficult the control design and even reduce the useful time of life.

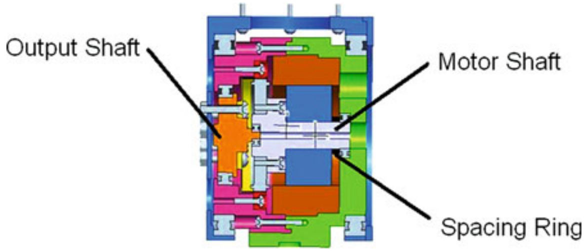


Fig. 1 Cross-section of a revolute joint designed by following the proposed guidelines

Alignment of Components

Components that rotate around a same axis, but are not assembled with each other, must be lined up ensuring no offset between their local rotation axis. Figure 1 shows the cross-section of a revolute joint as part of a robotic system. Note that the mechanical design of this joint has been developed to obtain a compact and robust structure. A correct alignment between joint shafts ensures the cancelation of vibration produced inside the joint body.

For example, an offset between motor shaft and output shaft yields reaction torque between components that can break some of them at high rotational velocities. One solution can be making the shaft concentric. A feature in the fully-left tip of motor shaft of Fig. 1 allows fitting the fully-right tip of output shaft inside the motor shaft through a ball bearing. The ball bearing allows the relative movement between motor and output shaft. Similarly, the joint housings have been designed in order to keep the components aligned. The motor housing presents a slot feature on the external diameter that permit to install the output shaft housing. The output shaft housing presents a projection that can be introduced in the slot feature of the motor housing ensuring the alignment.

Friction Avoidance

Friction in mechanism joints introduces no linearity in the dynamic formulation since the friction angles must be computed by using trigonometric functions (Rao and Dukkipati 2006). The methods of linearization require high computational efforts, thus cancelling frictions in the mechanical design is a suitable solution that simplifies the control architecture (Armstrong-Hélouvry 1991). Figure 2 shows examples of two revolute joint designs, in which two different solutions have been assumed for providing relative movement among components. In particular, the joint design of Fig. 2a contains bronze bushes that generate high friction leading to loss of mechanical energy (Nava Rodríguez 2010). Other devices can be used in order to reduce friction as much as possible, for example ball bearing, as shown in Fig. 2b. Note in Fig. 1 the proposed joint contains ball bearing that permit a low-friction movement among components. Rolling bearing can also be used in

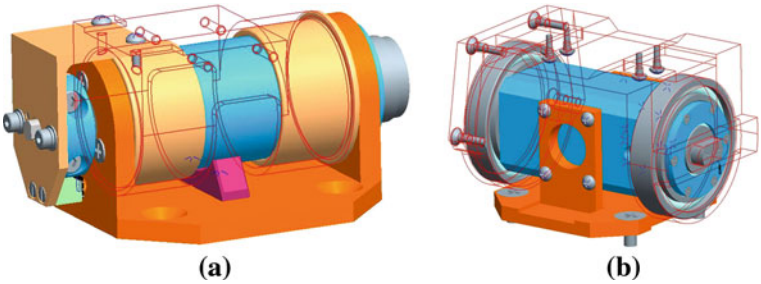


Fig. 2 Revolute joints with different levels of friction (Nava Rodríguez 2010): **a** high-friction design; **b** low-friction design

application in which the just transversal loads are required to be resisted (SKF homepage 2010). In some cases, the design requirements include the resistance to both high axial and transversal loads as well as bending torques. Four-point contact ball bearing can be a feasible solution for this problem (SKF homepage 2010).

For example in the joint design of Fig. 1, a four-point contact ball bearing is used to support the output shaft withstanding the external forces thus protecting the gearbox. Harmonic-Drive gearbox is selected for Fig. 1 joint and it does not present resistance to high external forces (HD Homepage 2010).

Vibration Avoidance

Vibration is a mechanical phenomenon that gives unfeasible oscillatory movement to a structure. Several strategies have been used in order to avoid the effect of vibrations (Bachmann et al. 1995). In the control issue, the vibration does not allow the system reaching the stable state, thus a frequency control can be applied. Nevertheless, vibration can be a white noise that presents variable amplitude and frequency. Under this condition, the control architecture requires complex code to resolve this problem (Preumont 2002). The vibration problem can be studied in two ways, such as joint level and whole structure level. At joint level, the components of the internal structure should be assembled compactly avoiding any clearance among them. Components like the spacing ring of Fig. 1 ensure the compactness of the joint structure. Similarly, bearings can also be used to joint components that rotate with different characteristics in a compact way, as shown in Fig. 1. At whole structure level, the design should be carried out in order to obtain similar dimensions of transversal area for the mechanism links. For example, Fig. 3a shows an arm design in which dimensions reduction of the transversal area can be noted at elbow and wrist. Vibration concentrations will appeare at these points since as long as the transversal area is small the vibrations are increased (De Silva 2007). The robotic arm of Fig. 3b presents a compact design in which the dimensions of transversal area are quite similar along whole structure.

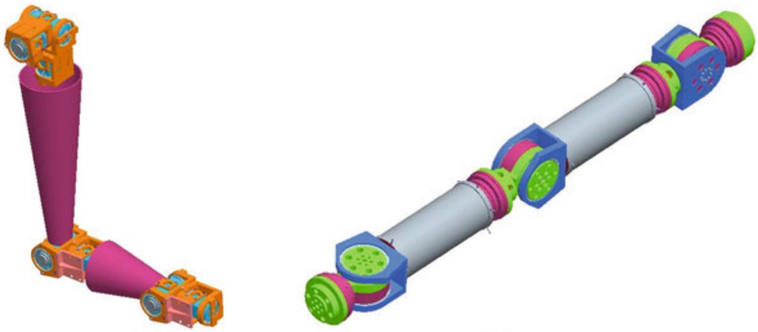


Fig. 3 Robotic arms designs: **a** a 3D-CAD scheme of an arm structure; **b** an arm design with robustness and compactness

Moreover, this design has been conceived as modular with the actuation separated in three groups: shoulder, elbow and wrist. The shoulder group contains the shoulder pitch and yaw as well as the upper-arm roll actuators, the elbow group contains the elbow pitch and the forearm roll actuators and the wrist group contains the wrist pitch and roll actuators. These groups are joined by two cylindrical links.

The aim of the modular design of the robotic arm of Fig. 3b is to obtain a robust and compact design avoiding vibrations.

The use of screws as jointing elements increases vibration in a structure (De Silva 2007). Therefore, a novel solution can be used as special glue to joint components, but this method does not alloy disassembling the structure. Nevertheless, the mechanical assembly can be studied in order to apply glue in some components installation without interference in the disassembly. Thus, the number of necessary screws for the whole assembly is reduced as well as the vibration level.

Cantilever Avoidance

Using two contact points to support a structure is strongly recommended. To use only one supporting point yields a cantilever structure that present bending torques around the support. The structure flexion generated by the bending torques provides an offset between the computed position of the end-effector and the real position. In some robotic applications, in which high accuracy is necessary, the structure flexion can represent difficulties that control system should compensate (Sciavicco and Siciliano 2005). Nevertheless, this compensation is not necessary if structure flexion is cancelled. Some examples of designs in which the cantilever is avoided can be recognized in Figs. 1, 2b, 3b, 4. In particular, note the joint structure of Fig. 1 corresponds to the shoulder yaw, elbow pitch and wrist pitch

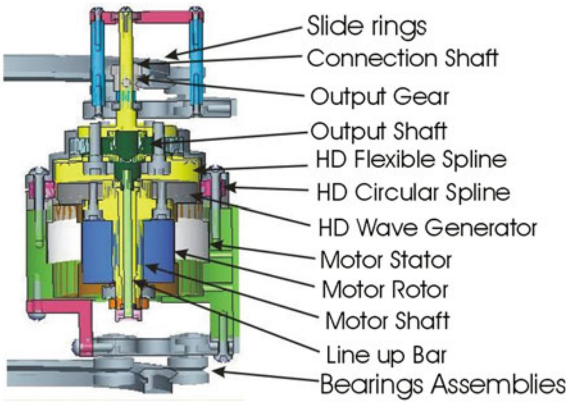


Fig. 4 Cross-section of a revolute joint indicating its main components (Nava Rodríguez et al. 2009)

joints of the robotic arm of Fig. 3b. The components that provide the connection among these joints and the robot structure are supporting in two points by proper ball bearing, as shown in the cross-section of Fig. 1. Similarly, Fig. 2b shows a joint design with two ball bearings supporting the component, transparent in Fig. 2b, which works as interface with the rest of the structure.

In other way, the interface of the joint model of Fig. 2a, in transparent, is connected to the output shaft by a component in cantilever. This component can flex reducing the accuracy of the structure. Finally, Fig. 4 shows a cross-section of a revolute joint that actuates a slider mechanism. The joint structure is supported by two pulleys and slide rings ensuring the robustness of the design. Similarly, the connection shaft is supporting two points in order to avoid flexions.

Backlash Avoidance

Backlash is a well known problem that reduces the accuracy of a robot operation. Backlash and Coulomb friction in combination with compliant gears, couplings and shafts render it difficult to achieve high-precision speed, position and force control in pointing and tracking systems (Troch et al. 1991). The necessary procedure that the control strategy should follow to cancel backlash can be saved with a compact mechanical design. Passive components as transmission elements, like wires and belts, can be useful as compliance elements (Zinn et al. 2004) but they can slip and flex producing position offsets between motor and output shafts. Therefore, using articulated mechanism as transmission elements can be a successful solution to this problem. The vision system of Fig. 5a uses the four-bar linkages of Fig. 5b to transmit tilt and pan actuations to the eye. The articulated mechanism of Fig. 5b has been designed carefully in order to obtain enough stiffness, compactness as well as avoiding cantilever by its "sandwich" configuration (Following bar between two pieces).

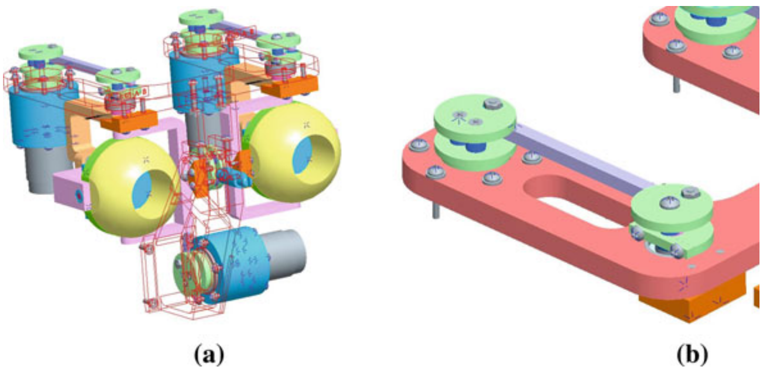
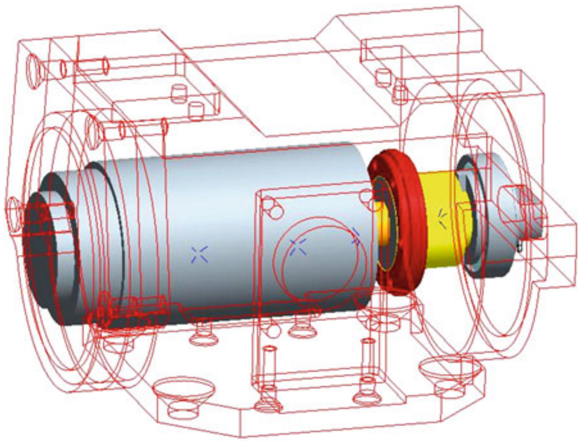


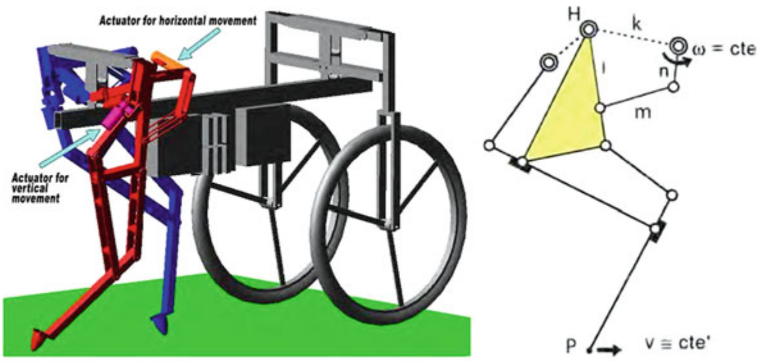
Fig. 5 Mechanical structure of a vision system (Nava Rodríguez 2010): **a** overview of the whole design; **b** detail of the motion transmission system

Fig. 6 Actuation system of a revolute joint with low-backlash (Nava Rodríguez 2010). (Joint structure in transparent)



Gearboxes can provide backlash since clearances can exist among gears. Harmonic Drive can be a good solution to avoid backlash produced by gearboxes since they are low-backlash devices (HD Homepage 2010).

Figure 6 shows the actuation system of a revolute joint that uses Harmonic Drive as gearbox. Note the output shaft directly driven by the flexible spline of the Harmonic Drive (HD Homepage 2010) in a compact configuration. Similar, the motor shaft actuates directly the wave generator of the Harmonic Drive (HD Homepage 2010) avoiding any backlash that can yield. Nevertheless, it is important to point out that Harmonic Drives are high cost devices because of their high performances and sometimes they cannot be assumed by some projects.



(a) (b)

Fig. 7 Suitable design of a walking robot (Gonzalez et al. 2010): **a** model of a virtual robot; **b** kinematic scheme of legs

Suitable Synthesis of Mechanism

As long as the mechanical structure is no complex the control architecture will be no complex as well (Gonzalez et al. 2010). Therefore, the synthesis of the robot mechanics should be addressed to obtain mechanisms with reduced number of links and DOF as well as high performance. For example, Fig. 7 shows the mechanical design for easy and fast operation of a walking robot. In particular, Fig. 7a shows a 3D-CAD model of the walking robot that represents the first solution that has been obtained by following this procedure. In the hybrid robot of Fig. 7a the problem of lateral stability was disregarded by adding two rear wheels instead of back legs. Therefore, the robot is composed of two articulated legs, as front legs, and two passive wheels, as back legs. These rear legs are fixed for movement on flat terrain but they will be controlled in future to overcome obstacles (Gonzalez et al. 2010). Figure 7b shows a scheme that improves the performance of previous scheme by adding a new four-bar mechanism The new four-bar mechanism has been synthesized as a function generator by using four-point Freudenstein equations. The points in the function generation have been chosen in order to obtain a constant velocity of point P in the central part of the trajectory, specifically within the central 600 mm, that is the rated step length of the mechanism. Despite this rated value, the leg is capable of taking shorter or longer steps (up to 1 m). Far from the conditions in which the synthesis has been made, the trajectories are not straight lines and there is some coupling between vertical and horizontal movement. However, this coupling does not interfere with the good execution of the step in normal operation. A more complicated control of the trajectories is required when it is necessary for the leg to overcome an obstacle (Gonzalez et al. 2010).

In some cases, the study of nature can be useful in order to obtain successful mechanism with suitable characteristics (Ceccarelli et al. 2005), for example in the design of anthropomorphic and zoomorphic systems.

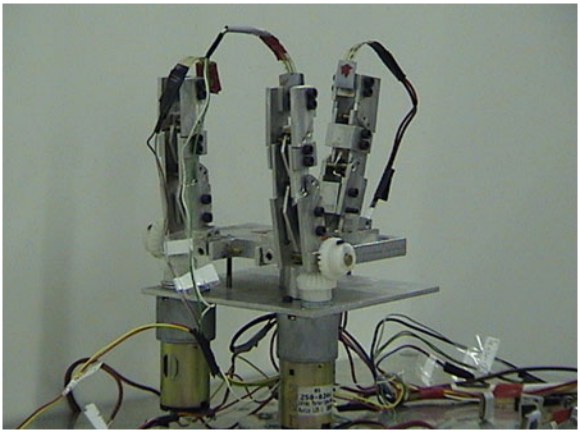


Fig. 8 Robotic hand with three-one DOF articulated fingers (Nava Rodríguez et al. 2004)

Figure 8 shows an overview of a robotic hand with three-one DOF articulated fingers. The design process of this robotics hand has been developed by studying the human hand performance (Nava Rodríguez et al. 2004), (Ceccarelli et al. 2005), (Ceccarelli et al. 2006), (Nava Rodríguez et al. 2006) since for the design of an anthropomorphic hand a suitable knowledge of the human grasp is needed. Cylindrical grasp of human hand has been analysed since it represents the most used grasp in industrial applications (Cutkosky 1989). In particular, dimensions of fingers, grasping forces and contact points between fingers and objects have been investigated in human grasping. The dimensions of each phalange of index, medium and thumb have been measured for five persons (Nava Rodríguez et al. 2004). Figure 9a shows a photo sequence of a cylindrical grasp performance of a human hand. The positions of marks of human hand fingers of Fig. 9a have been measured in order to achieve this position by the robotic hand of Fig. 8. The force measuring system of Fig. 9b has been set up in a human hand for developing the experimental test of Fig. 9c. The grasp forces of several objects with different shapes and dimensions have been measured in order to compare results with experimental validations of the robotic hand of Fig. 8. The experimental results show the practical feasibility of the prototype as three-fingered robotic sensored hand with three 1 DOF anthropomorphic fingers, having human-like operation (Nava Rodríguez et al. 2004). The human-like characteristics of the robotic hand of Fig. 8 simplify its control architecture since some aspects of grasp have been checked in the mechanical design, for example performance of fingers and grasping force.

The robotic device of Fig. 10 is another example of a system inspired in the study of human body. This device has been used for rehabilitation of injured human wrist. The chosen class of mechanical solutions is based on a serial structure, with direct drive by the motors: one motor drives the pronation/supination, one motor the flexion/extension and two parallely coupled motors the abduction/adduction.

The main features of this arrangement are: 1) good rigidity of the structure; 2) direct drive of the manipulandum, which eliminates any backlash in the force/motion transmission; 3) minimization of the overall inertia, because most of the

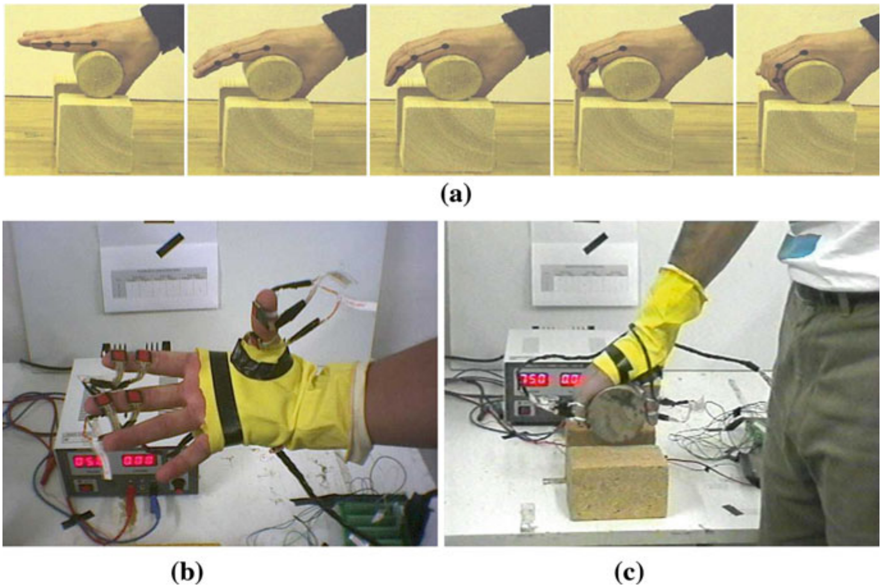
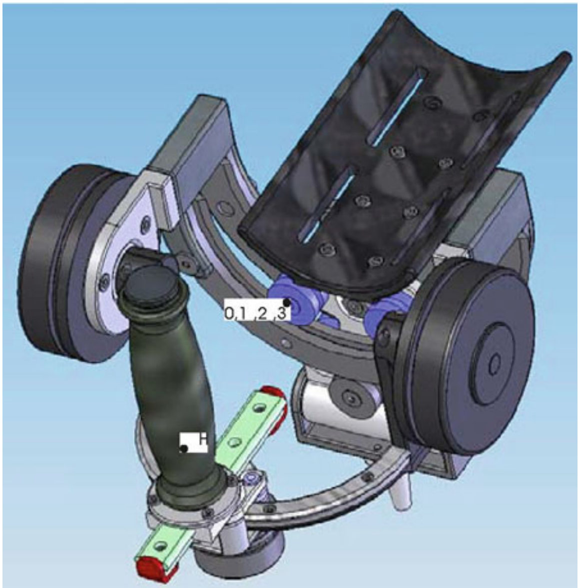


Fig. 9 Study of the human hand operation for an anthropomorphic design (Ceccarelli et al. 2006): **a** photo sequence of a cylindrical grasp performance with joint marks; **b** measuring system of grasp force; **c** experimental test of a human firm grasp

Fig. 10 A robot for rehabilitation of wrist injury (Masia et al. 2009)



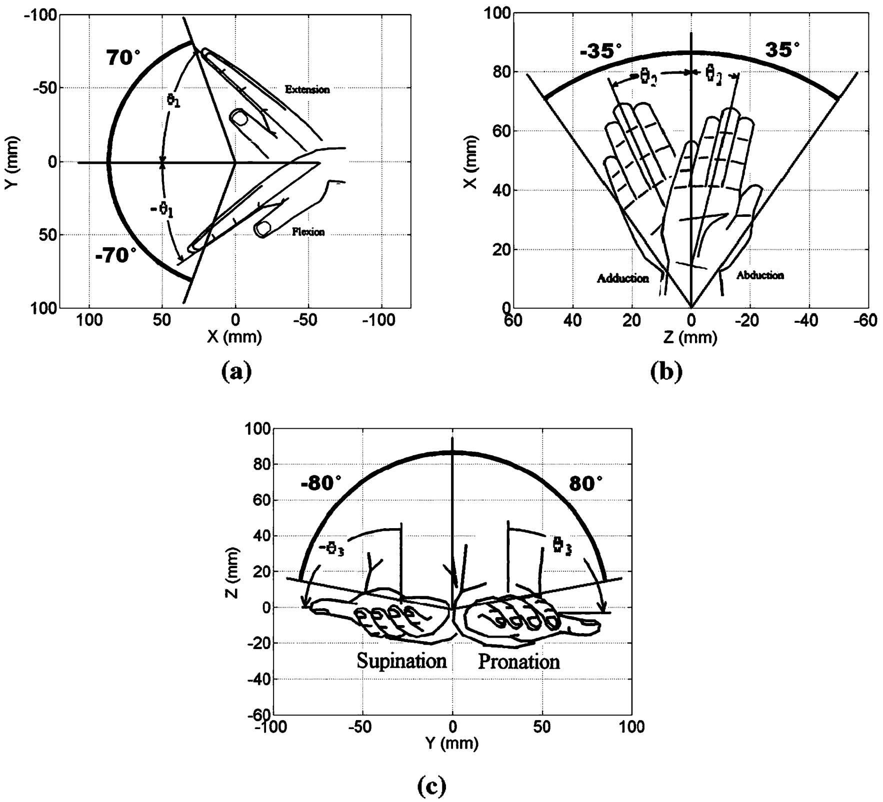


Fig. 11 Study of the human wrist movements for an anthropomorphic design (Masia et al. 2009)

mass is either fixed, or close to the rotation axes; 4) independence of each single DOF (Masia et al. 2009).

The ranges of motion for each DOF have been fixed based on the human wrist capabilities. Figure 11 shows plots of human wrist movements, in which ranges of motions can be recognized. Thus, the mechanical design of the wrist robot of Fig. 10 has been constrained to move from −70° to 70° for flexion/extension, from −35 to 35 for abduction/adduction and from −80 to 80 for pronation/supination. A suitable adaptive control has been implemented in the robot wrist in order to maximize task complexity as a function of the level of performance. It induces the patient to maximize the ability to face complex tasks while minimizing the reliance on robot assistance (Masia et al. 2009).

Particular Cases

Particular systems, for example vision or cognitive systems require to work under certain condition that do not interfere with their correct operation. In this case, an

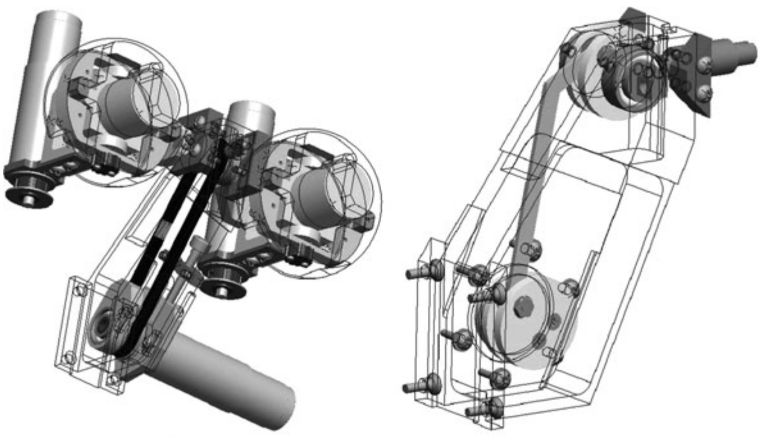


Fig. 12 Vision system of the humanoid robot iCub (Nava Rodríguez 2010): **a** current design with belts mechanism for the motion transmission; **b** proposed solution based on articulated mechanism

interdisciplinary group of work is necessary to design the mechanical structures that contain these particular systems. The mechanical designer needs a feed-back from expert in every discipline in order to identify the possible problems that the structure can generate to the particular system, for afterward resolving them. For example, vision is a system that requires to work under high accuracy condition, in which some external effects can interfere with its proper operation. Figure 12a shows the structure of the current vision sub-system of the iCub Humanoid robot (Sandini et al. 2005). From discussions with vision experts, the following design problems have been identified in the current iCub eye sub-system (Nava Rodríguez 2010):

– The belt system presents slippage and backlash since the force is transmitted by the contact between belt teeth.
– In highly dynamic applications, the belt system can generate some vibrations, unsuitable for the vision system, which requires frequent adjusted of tension.
– The fact that the tilt motor has to carry the pan motors slows the system down.
– A small amount of backlash is always necessary to reduce excessive wear, heat and noise created by the current gearboxes.

Figure 12b shows the proposed solution to the slippage, backlash and vibration problems of belt system that involves an articulated mechanism to transmit the motion from motor to eye tilt and pan. An articulated mechanism is a robust solution that provides feasible stiffness to the mechanical structure, as also reported in backlash avoidance section. The parallel manipulator that composes the eye structure of Fig. 5a can be a solution to the problem generated for the serial configuration of the eye kinematic chain. This parallel mechanism allows the

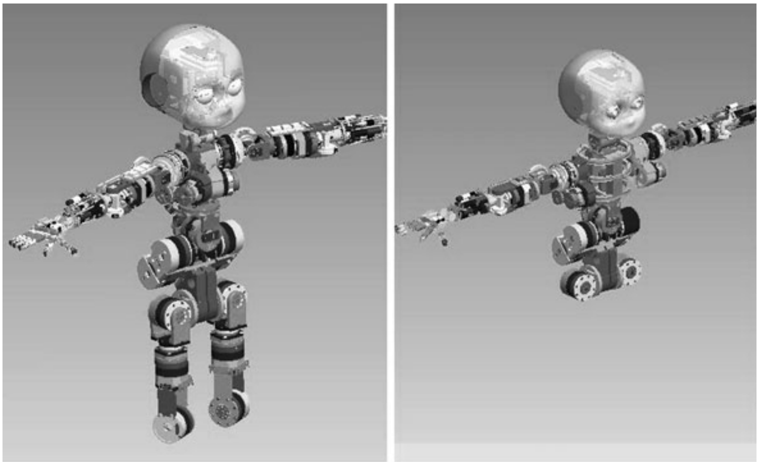


Fig. 13 3D-CAD model of the iCub humanoid robot: **a** current design; **b** a design including a chest mechanism

end-effector movement in a proper range for artificial vision with the motor fixed to the base frame. Finally, Harmonic Drive can replace the current gearboxes in order to cancel backlash, as reported in the backlash avoidance section.

Therefore, considering the above-mentioned problems of the iCub vision system from the mechanical design, the vision can perform an operation that does not require significant compensation from the control system.

Figure 13 shows a 3D-CAD model of the humanoid robot iCub that is the result of the European project RobotCub, which focuses on the development of artificial cognitive systems in humanoid robotics (Sandini 2005). In a cognitive system, as long as the mechanical structure is human-like the system operation will be closer to the human being performance. Figure 13a shows a model of the current upper-body of iCub that presents 3 DOF for trunk in serial configuration and 6 DOF for each arm in serial configuration too. In the kinematic chain of iCub upper-body, an extra DOF that achieves the human chest operation is required for a closer human-like structure. Figure 13b shows a model of a proposed chest mechanism that achieves the functions of both Pectoralis Minor and Upper Back human muscles in a whole compact structure (Nava Rodríguez et al. 2009). Figure 14a shows in detail the proposed chest mechanism for iCub structure and Fig. 14b shows a kinematic scheme of arm sub-systems including the chest DOFs. Note that the characteristics of the chest structure of Fig. 14 include the guidelines that has been reported in this chapter, such us vibration, backlash, cantilever and friction avoidance as well as alignment of components. The development of a cognitive system involves the learning of human task by the robot system. The learning process of a robot with movement capabilities constrained by a limited kinematic structure is more difficult than a robot with the kinematic chain closer to that of

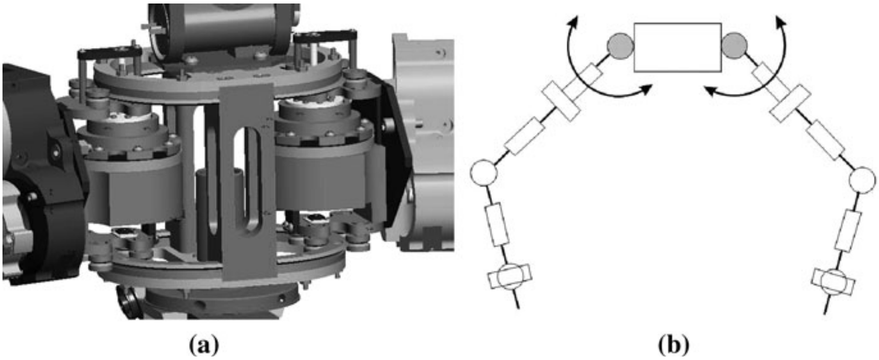


Fig. 14 Chest mechanism structure proposed for iCub humanoid (Nava Rodríguez et al. 2009): **a** overview of the whole design; **b** kinematic scheme

human body. Therefore, the computational efforts of the iCub control system for achieving cognitive operation of manipulation has been reduced by considering the proposed chest mechanism of Figs. 13b and 14.

3 Conclusions

Some important guidelines have been presented for an accurate mechanical design that provides characteristics for development of not so-complex control architecture. Problems like backlash, vibration, high friction, cantilever and offsets among components, which can interfere with a proper operation of a robot system, have been resolved by proposing suitable solutions from the mechanical point of view. Usually, these problems could be resolved by the control architecture that requires complex strategies of linearization and compensation as well as high computational efforts. Nevertheless, the proposed mechanical improvements are effective and can be applied in a practical application in a built system. Simplifying the dynamic formulation that control system must compensate, by simplifying the kinematic chain, is a feasible way to reduce the complexity of the control system. A proper synthesis of the robot mechanisms yields a kinematic chain with adequate links and DOFs for a successful operation. Finally, to mimic the performance of accurate/optimized systems is a suitable way to optimize the robot operation and reduce the control architecture compensation. For example, the human body is a high optimized machine since its centuries of evolution and it can represent a good model for mimicking performance.

The modern research involves the participation of experts in different fields composing a multidisciplinary group for the development of complex systems like humanoid robots. Some mechanical solutions applied to the structure design can interfere with the proper operation of certain complex systems. These solutions can be successful from the mechanical point of view but their characteristics cannot be proper in specific applications. Therefore, feed-back from expert of other research lines is necessary for the mechanical designer.

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