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## Using Parallel Platforms as Climbing Robots

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### 1. Introduction

Primates are the living beings with a greater capacity of manipulation. This skill derives from they have two legs equipped with elements adapted to the manipulation and grasping. The simultaneous use of both legs and arms confer to these living beings their special features to manipulate and manage different objects. As many technical developments inspired when nature laws are observed, parallel robots are conceived in a similar way. In this way, the mechanical structure of a parallel robot is composed by a closed chain in which the end effector is linked to the basis at least by two independent kinematic chains.

This definition can be in conflict with the developments about coordinated robots that also constitute closed kinematic chains. Parallel robots simplify these chains in such a way that every one has only one actuator. So, the complexity of the mechanism can be reduced and it is possible to make good use of the energy provided by the actuators to obtain a higher payload capacity or to increase the speed of movement of the end effector.

The first theoretical works on mechanical parallel structures appear long time ago, even before the notion of robot. In this way the first parallel mechanism was patented in 1931 (US Patent N° 1789680) and was designed by James E. Gwinnett (Gwinnett 1931). In 1940 Willard Pollard presented a robot with 5 degrees of freedom dedicated to painting tasks. The robot was composed of three legs of two links each one. The three actuators of the base drive the position of the tool.

However, other more significant parallel mechanisms have been achieved from then. In this way, in 1947 Eric Gough designed the most popular parallel platform. Nowadays numerous platforms can be found with the name of MAST (Multi-Axis Simulation Table). In 1965, Mr. Stewart (Stewart, 1965) described a movement platform of 6 degrees of freedom (dof) designed to use as a flight simulator. On the contrary to the general belief the Stewart mechanism is different to the previously presented by Gough. The work presented by Stewart had and have a great influence in the academic world, and it is considered one of the first works of analysis of parallel structures.

At the same time, Klaus Cappel carried out in the Franklin Institute Research Laboratory a lot of researches with parallel platforms of 6 degrees of freedom. In 1967 Cappel patented a motion simulator based on a hexapod (Cappel, 1967). Later, in 1978 Hunt (Hunt 1978) suggested that the mechanisms of the flight simulators can be used as parallel robots. Also Hunt pointed out that parallel robots required a more detailed study in the context of robotic applications due to the advantages of accuracy and rigidity of these platforms.

Besides an excellent relation payload/dead weight, parallel robots have other interesting features. In 1979, McCallion and Pham (McCallion and Pham, 1979) suggested to use the Stewart platform as a parallel robot in an assembly robotics cell, basically due to the end-effector is much less sensitive than serial robots. The rigidity assures that the distortions in the actuators are minute and produces a high accuracy in the pose of the robot.

In this paper we present some parallel robots designed and developed to climb along several structures as pipes, tubular or metallic structures. The parallel robots proposed can climb on inside or outside tubular structures or palm trunks. Also a parallel robot with light modifications has been developed to climb on metallic structures of bridges or dome of buildings. Therefore, the purpose of this paper consists of showing the promising applications that are possible to achieve using parallel robots as climbing robots.

The remainder of the paper is structured as follows. In the next section the main features of parallel robots will be presented and discussed. Different possible configurations and morphologies of the parallel robots will be suggested. In the third section the kinematics and dynamics analysis of the parallel robots are analysed. In a following section some prototypes of parallel climbing robots will be shown. The main features of these robots will be analyzed and discussed. In section five, other parallel robots developed taking into account the initial structure of the first prototype of parallel climbing robot developed will be presented. Finally, some conclusions and future works will be proposed.

## 2. Main Features of Parallel Robots

Without a doubt, the present supremacy of the serial robots as opposed to parallel robots is patent taken into account their sales volume. However, parallel robots present a constant increasing tendency since some years ago. Nowadays, parallel robots are used in multiple applications due to present many advantages that make them especially suitable to resolve many problems in which serial robots have some important limitations.

With the purpose of comparing both platforms we can express the following advantages of the parallel robots:

- Power actuators are directly connected to the base of the robot with the end effector. So, power actuators serve as structural elements conferring high load capacity even more than its own weight. This way, these platforms have a high proportional ratio of its payload and deadweight providing a high energetic efficiency.
- Parallel structures are platforms capable to reach high velocities and develop big forces with a very important advantage: the low cost of manufacturing (Lazard, 1992).
- Parallel platforms are mechanically less complex than serial robots.

However, also parallel robots present some features that, depending on the application can be considered as disadvantages:

- Kinematics of parallel robots is more complicated. In some occasions redundant sensors are necessary to control the system.
- Working space is difficult to calculate due to the position and orientation of the end effector are extremely coupled. Several works have been reported about the position and orientation workspace of these platforms (Huan et al., 1999 & Almonacid et al. 2001).

- Possible singularities are very complex to analyze. Singularities should be analyzed specifically for every topology of parallel robot.
- A general dynamic model for the parallel robot is difficult to obtain in opposite of linear robot. For these reason, parallel robots are controlled nowadays in a decoupling manner.

### 2.1 Possible configurations of parallel robots

Many possible configurations of parallel robots can be designed. The high volume of possible combinations of kinematic chains, joints, restrictions of the joint movements, etc., make actually impossible to systematize all possible structures of parallel robots.

Merlet (Merlet, 1997) proposed a first sorting taking into account the movements that parallel robots can to accomplish. Two groups can be differentiated: planar robots and 3D robots. The movements of planar robots are reduced on a plane. Therefore they can have 2 or 3 degrees of freedom (a linear movement in the plane and a rotation movement along one axis perpendicular to the plane). Figure 1(a) shows some of possible configurations of planar parallel robots. However, 3D parallel robots can work in all 3D space. Figure 1(b) shows some of them with different degrees of freedom. In all of them universal (U) or spherical (S) joints with two and three dof respectively have been considered.

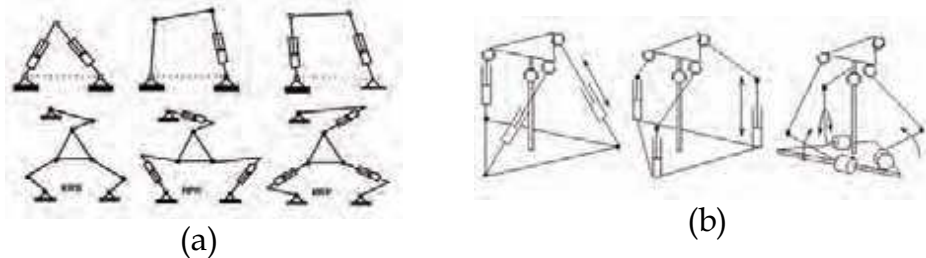


Fig. 1. Planar parallel robots with 2 and 3 dof (a); and 3D parallel robots (b).

### 2.2 Morphology of the parallel robot proposed as climbing platform

The morphology of the parallel robot proposed to climb along different structures is formed by two parallel rings of 6 dof. The main structure of the robot is similar to the classic structure of the parallel robot based on the Stewart-Gough (S-G) platform (Galt 1997; Merlet 1997). This platform consists of two rings linked by six linear actuators as UPS kinematic chains (Universal-Prismatic-Spherical joints) (see Fig. 2).

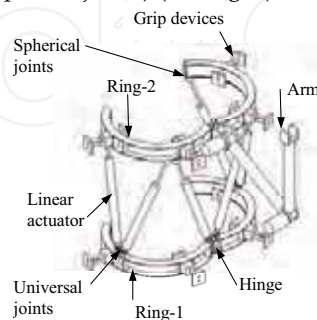


Fig. 2. Mechanical design of a parallel robot to climb along tubular structures.

On this general morphology several modifications can be accomplished with the purpose the robot can climb along other structures. In this way different legs can be added on each one of the external rings of the robot with the purpose the parallel robot can work outside wall of pipes. These legs allow fastening one ring to the pipe while the other ring moves along the structure. These modifications will be discussed in Section 4.

### 3. Mathematical analysis of parallel robots

Kinematic models of parallel robots present essential differences with regard to serial robots. In serial robots a systematic methodology exists providing a direct kinematic model of the robot independent of its configuration. Inverse kinematic models are more complex and it is necessary to take into account geometric restrictions for each configuration, or to resolve equations by numerical methods and so providing different solutions in some occasions. Otherwise parallel robots present the inverse problem. Inverse kinematic model is easy to obtain taking into account geometric restrictions, while direct kinematic model presents a greater complexity.

Many authors have been proposed different methods to provide kinematic models for parallel robots (Fitcher, 1986; Merlet 1990). In this way Fitcher provided the kinematic equations of general platform (Stewart platform) and also dynamic equations were anticipated. Merlet considered some design aspects of the Stewart platform providing some guidelines to resolve the kinematic equations and the jacobian. Also the dynamic equations were extended.

In the following subsections kinematics and dynamics aspects of parallel robots will be discussed. We have chosen for this discussion a parallel platform of six dof as presented in figure 3.

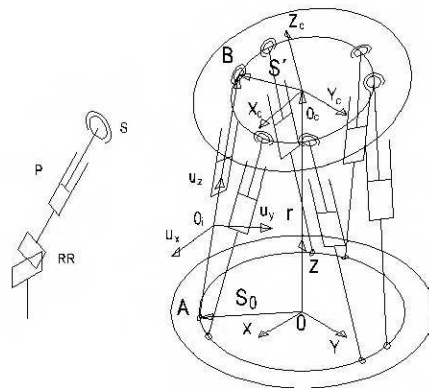


Fig. 3. General structure of a parallel platform with 6 dof.

#### 3.1 Inverse Kinematic Model

The inverse kinematic solution in a parallel robot as described in previous section, can be defined by the set of equations that express the joint values of the kinematic chain depending on the configuration of the end effector. The approach of such equations can be expressed in a vectorial way. Taking as reference the system of figure 3 representing a parallel robot with 6 dof with UPS kinematic chains, for each chain we can express:

$$\vec{r}^i = \vec{r}_1 + A_1 \vec{s}_1^i - \vec{s}_0^i \quad i = 1, \dots, 6 \quad (1)$$

where:

- $A_1$  is the rotation matrix that represents the orientation of the basis
- $\vec{s}_1^i$  and  $\vec{s}_0^i$  are position vectors that locate universal and spherical joints with respect to base reference frame and mobile ring
- $\vec{r}_1$  is the position vector of the mobile ring expressed in the reference frame of the base
- and finally  $\vec{r}^i$  is the vector of each one of the linear actuators.

These six equations constitute the inverse kinematics model in which the length of the actuators are the module of the vector  $\vec{r}^i$ . As can be observed, this methodology produces, except singular configurations, the solution in an easy way. In some singular cases, several solutions can be provided in a similar way than the serial robots.

### 3.2 Direct Kinematic Model

The direct kinematic model, or in other words, to calculate the position and orientation of the mobile base from the length of the actuators is a more complicated problem. Analytical solutions to this problem only have been found in some easy configurations making use of the Denavit-Hartenberg formulation or with geometric restrictions (Innocenti & Parenti-Castelli, 1993; Ait-Ahmed & Renaud, 1993). To achieve the solution for more complex configurations it is necessary to employ numerical methods (Almonacid et al., 2003). These methods provide higher degree polynomial solutions with multiple solutions. Other authors (Bonev & Ryu, 1999) proposed a practical solution consisting of employing redundant sensors to resolve the direct problem. These extra sensors allow to achieve the pose of the robot. However this solution entails additional problems and is difficult to carry out.

A better solution consists of employing multibody formulation (Saltaren et al., 2004). This method provides an easy computational solution at the same time that provides a systematic methodology independent of the robot configuration. Also in case of exit the method provides only one solution. However the method presents important disadvantages due to it is necessary to assure the convergence and the solution is very sensitive to initial conditions.

### 3.3 Dynamic Model

As well as the kinematic model, the dynamic model of parallel robots presents important differences with regard to serial robots. Parallel robots do not present a general equation that defines its dynamic behaviour as serial robots are:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau \quad (2)$$

Some suggestions have been presented based on Newton-Euler formulation (Dasgupta & Mruthyunjaya, 1998; Tsai 1999), but all of them take into account some distinctive features and lead to computational algorithms with an indeterminate efficiency.

The most interesting and employed formulation, comes from the multibody dynamics using the Newton-Euler equations along with the Lagrange restrictions. Through this formulation the inverse and direct dynamics problem can be resolved in an efficient manner. This formulation employs the following equations:

$$\begin{aligned}
 M\ddot{q} + \Phi_q^T \lambda &= Q \\
 \Phi_q \dot{q} &= v \\
 \Phi_q \ddot{q} &= \gamma \\
 \Phi &= 0
 \end{aligned}
 \tag{3}$$

Where:

- $q$  is the generalized position of the system
- $Q$  are the external generalized forces applied to the system
- $M$  is the generalized mass matrix of the system
- $\Phi$  is the movement constraint vector
- $\lambda$  is the vector of variables of Lagrange
- $v$  is the velocity vector
- $\gamma$  is the acceleration vector

To resolve the last equation it is necessary to employ numerical methods. As a consequence, an analytic dynamic model can not be derived.

### 3.4 Control of Parallel Robots

The non-existence of analytics dynamics models of the parallel robots produces a great difficulty to approach general control algorithms for them. The control systems proposed until now are relatively simple (not couple systems): the kinematics model generates references for the joints of the robot. In (Liu et al., 1992) some aspects with regard to the control parallel robots in the working space are discussed. However, the direct extension of control scheme to real time systems presents several problems due to the high computational cost to resolve the direct kinematic model. Another option consists of planning the path in the Euclidean space due to only the inverse kinematic model is required and this is easier to resolve.

In [Aracil et al., 2003] a control algorithm for a climbing parallel robot is discussed. The proposed scheme makes use of the information provided by ultrasonic sensors along with a double feedback loop, one for the control of the position of each actuator (designed with a PD controller), and the other one to centre de robot.

## 4. Climbing Parallel Robots

Using parallel robots as climbing robots offer a lot of possibilities. During last years several climbing parallel robots have been developed for using them in different applications. So, the use of Stewart-Gough platform as climbing robot to perform tasks in tubular structures such as oil pipes, bridge steel cables, towers and trunks of palm trees is very promising. The basic morphology is shown in figure 2. The platform is formed by two rings joined with 6 linear actuators as UPS kinematics chains (where the U degrees of freedom belongs to an universal joint, P is a prismatic degree of freedom that belongs to the linear actuator and S is the spherical joint). The robot assembly around the tubular structure is carried out through a system of hinges. The holding systems are based on a series of grip devices built in each ring. Those grip devices hold the reference ring firmly attached to the tubular structure while the free ring is displaced by the control system.

The automatic control of the robot that climbs along tubular structures should take into account geometrical changes in the path of the tubes. As a consequence, three  $120^\circ$  ultrasonic sensors were installed in every ring. The three sensors allow calculating the difference between the centre of the ring and the tube (Aracil et al., 2003). Based on this estimate, an algorithm to control the displacement of the moving ring can be done by maintaining it centred and following the curve of the tube automatically (Almonacid et al. 2003). The climbing process is composed by four steps working in sequence. The steps are shown in figure 4. It consists of holding around the tube and moving up by using holding systems attached to the rings. It displaces along the tube as one ring holds up and the other free ring moves on.

On this basis a climbing parallel robot was developed to climb on a palm trunk. In figure 5 several images show the robot in different positions of the palm trunk. The first version of this prototype designed to climb this kind of structures moved to a velocity of 0.4 m/s. It was composed of 6 pneumatic cylinders. Every cylinder is controlled through a proportional valve FESTO MPYE-5. A linear encoder measures its displacement. The gripping system, which is activated pneumatically, can be seen in every ring. A multi-axis Delta Tau PMC-VME card has been used for the control structure of the robot.

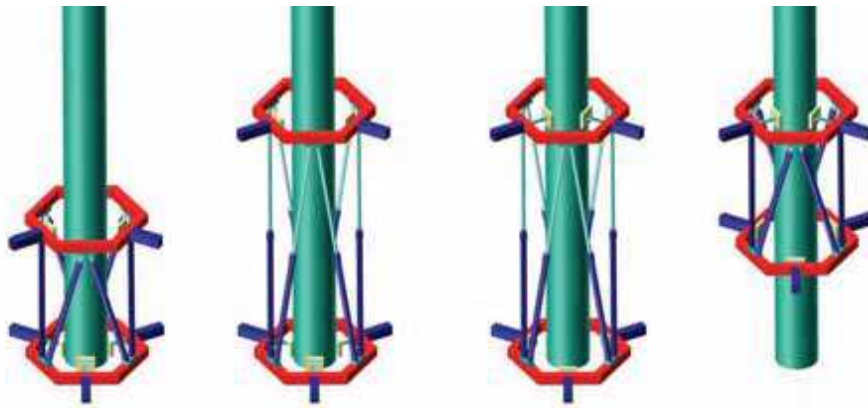


Fig. 4. Steps that define the climbing process of the climbing parallel robot.

But parallel robots also can climb inside tubes or pipes. To perform these tasks, it is necessary to modify some aspects like the holding systems and also the robot universal joints with the aim the robot was capable to have big rotations as observed in figure 6. These joints should be more mechanically robust in contrast to the standard universal joints (Aracil et al., 2006). As can be observed, the gripping system is radial to the rings.

Another possibility to climb along tubular structures as tubes or pipes is by means of a couple of arms that can be extended and retracted. This couple of arms is connected to each ring and serves as holding device. The main advantage of such holding system consists of the robot is capable of climb along complicated structures with obstacles due to its structural design. In this sense, the robot can adopt several forms and postures to overcome complicated zones as can be observed in figure 7.





Fig. 5. Different images of the parallel robot climbing o a palm tree trunk.

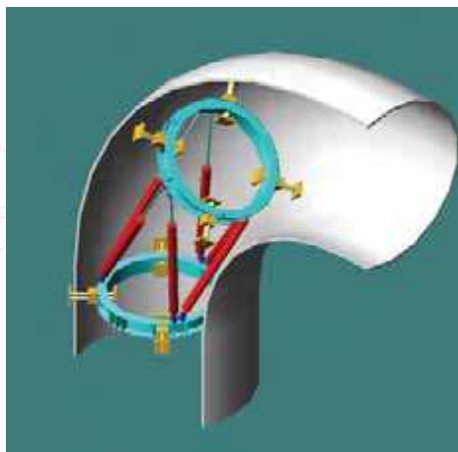


Fig. 6. Mechanical adaptation an parallel robot for climbing inside of tubes.

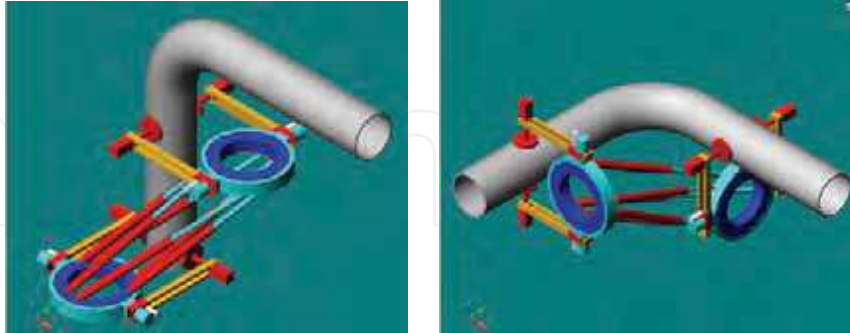


Fig. 7. Parallel robot climbing outside tubular structures.

A solution for the problem of displacement and climbing along metallic structures should theoretically be based on a mechanism whose power actuators are part of the structure, connected directly to the end effector and with a large geometric dexterity to overcome obstacles using minimal movements. Also, the robot should be lightweight, mechanically simple, with a large payload capacity and high velocity. Taking into account these features we have proposed a climbing parallel robot capable to develop tasks on such metallic structures. Following with the previous adaptations of the basic climbing parallel robot, also is possible using this parallel robot to climb along structural frames or metallic structures. In the development of this climbing parallel robot (CPR) it is necessary to carry out some modifications on the general platform with the purpose of facilitating the movements of the robot on such structures (Saltaren et al., 2005).

In contrast with the previous climbing robots used to work on palm trees with an interior clamping device to hold and climb by palm and pipes, the clamping devices of the robot should fold and extend at least in two predefined positions. The possibility of folding or extending the clamping legs allows reducing possible collisions between the movement ring and the environment. Moreover in some sequences of displacement it is necessary to orientate the legs of each one of the rings of the robot to predetermined positions ( $-90^\circ$ ,  $0^\circ$ ,  $+90^\circ$ ), because the rotation of the exterior ring with its clamping device may reduce the rotation requirements of both rings around its axes. For this reason it is possible to avoid the collisions between the linear actuators originated when they cross themselves in the displacement of each one of the two rings of the robot. So, with the purpose of allowing configurations of  $90^\circ$  between the rings that constitute the basis of the robot, the spherical and universal joints have been adapted and redesigned (see figure 8).

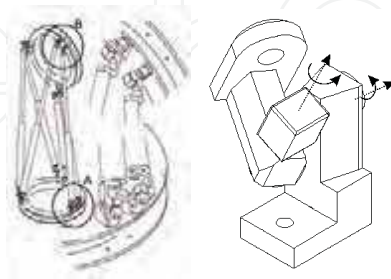


Fig. 8. Detail of the joints adapted with the purpose of the robot can accomplish postures of  $90^\circ$ .

The displacement of the robot can be carried out as a sequence of four simple movements. Figure 9 shows a sequence of these movements. This displacement is composed of four steps:

- The robot is grasped to the beam with both rings legs
- The robot is held by ring 1 legs. Ring 2 legs are released and folded. Linear actuators are commanded allowing ring 2 to acquire the required position.
- The ring that has been displaced (ring 2) is held through its clamping devices.
- With ring 2 grasped to the beam, ring 1 is released. Ring 1 acquires the new position. Once ring 1 has achieved the position, the robot is ready for a new cycle.

So, the postures to generate movements through a right path are simple and easily reachable. However, when it is necessary to overcome and pass structural nodes in the metallic structures, the robot must be able to acquire more complicated postures. A structural node is composed by three beams making a corner. In such structural nodes the robot can change the direction of its movement or can keep the same direction when passes it. In figure 10 several postures that the robot can adopt are presented. This sequence shows that the robot requires a minimum number of postures to pass a structural node.

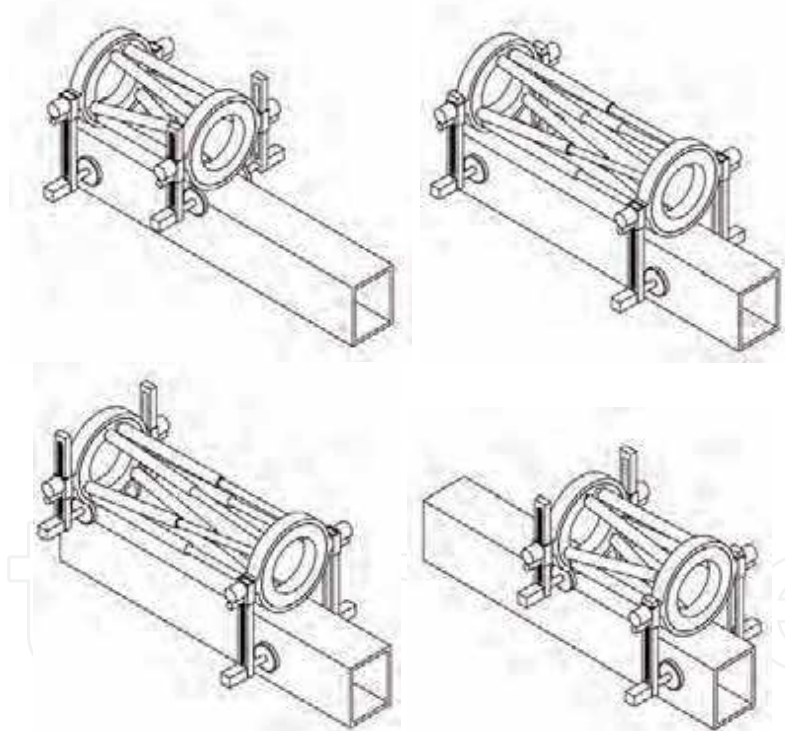


Fig. 9. Sequence of displacements of the robot along the length of a straight trajectory.

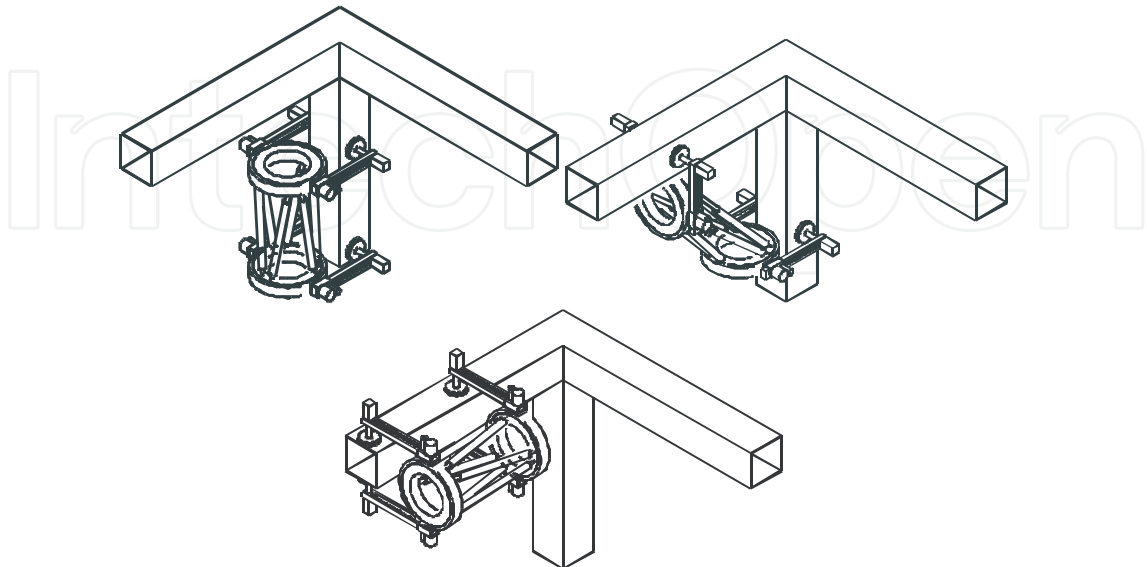


Fig. 10. Example of postures evading a structural node.

A detailed analysis of such postures is presented in (Saltaren et al., 2005). The Jacobian of the robot about each one of the postures is calculated. Also, based on the jacobian analysis, the angular limits of the upper ring can be calculated for each one of the postures of the robot. Such analysis shows the feasibility of using the presented parallel robot as climbing robot on metallic structures. Also the dynamic analysis of the postures needed to evade a structural node is presented and analysed.

Taking into account the results reported in (Saltaren et al., 2005), an electrical climbing parallel robot prototype has been developed. The main features of this prototype are: 300 mm of ring diameter, 490 mm of length actuators and a working velocity of 0.2 m/sec. The experimental analysis with this prototype showed the big potential of using parallel robot as climbing robot.

## 5. Other applications with parallel robots

The great variety of possible configurations of parallel robots produces that light modifications of such mechanisms allow their use in multiple applications. So, we can find parallel robots from micro robots to high platforms with a high payload, or from medical to spatial applications. Taking as basis the robot presented in figure 2 we have developed other parallel robots with special features depending of the application field.

Such is the case of ROBOTENIS parallel robot designed and developed with the purpose of making experiments of visual control systems (Angel et al., 2005). This robot can achieve a velocity of 2m/sec.

Also, other parallel robots making use of the capacity of adaptation due to their variable geometry have been designed, developed and tested. Such is the case of the submarine robot REMO (Aracil et al., 2005). The adaptation can be achieved through the six dof parallel platform. This parallel platform allows a great manoeuvrability

besides the possibility to achieve large depths due to its watertight volume is much reduced.

We have derived a second prototype of this robot (REMO II) with several improvements. We have added one motor in each ring to produce the driving forces. So, the navigation is based in the generation of driving forces due to the combination of forces produced by the motors mounted in the rings. This procedure allows achieving significant advantages with regard to the previous prototype.

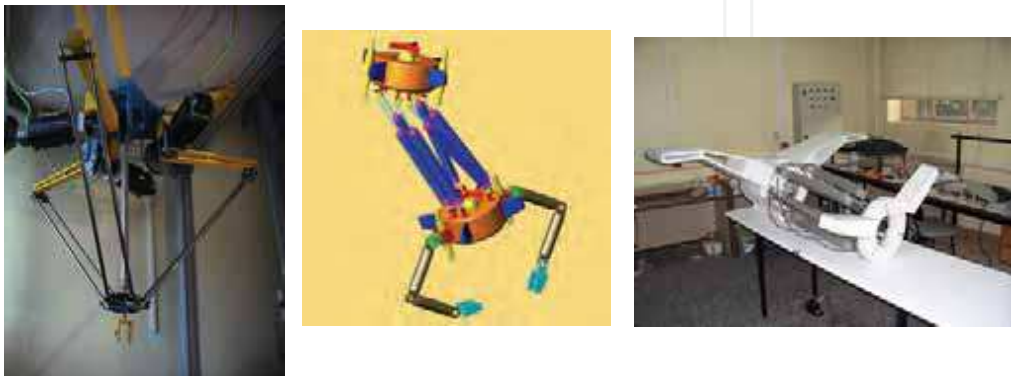


Fig. 11. Another parallel robots: ROBOTENIS (UPM), REMO (UPM) and REMO II (UPM).

## 6. Conclusions and Future work

At present, parallel robots show a great progress in their development due to their behaviour in multiple applications. In this sense, the Stewart-Gough platform with proper mechanical adaptations could be used for a climbing parallel robot. A climbing parallel robot with 6 degrees of freedom has been proposed and analysed. Parallel robots have great advantages compared to serial robots with legs using as climbing robots. Some advantages can be cited as the high weight payload capacity, robustness, simplicity of its mechanical design, etc. However, some difficulties have to be resolved too as the adaptation to the structure meanwhile the robot accomplishes the task or the singularities that can be produced in the movement on the structure.

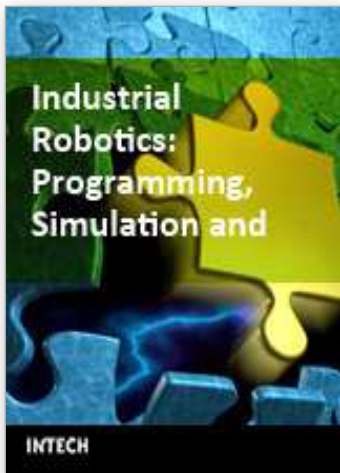
In this paper several options of a climbing parallel robot based in the S-G platform have been presented and analysed. First of all, an initial prototype to climb along tubular structures as pipes or palm trunks has been shown. The main features of this robot are the pneumatic actuators and the external control loop that allows centring the robot to the tubular structure. Taking into account this first prototype, another parallel robot to resolve the problem of displacement and climbing along metallic structures has been presented. The main features of this robot are the electrical actuators and the clamping device developed with the purpose of reducing possible collisions between the movement ring of the robot and the environment. The results achieved with both prototypes show the validity of these platforms to undertake tasks in which are necessary to climb on. In short, this paper tries to show the big potential of using parallel robots as climbing robots.

Also, we are working in introducing teleoperation techniques to manage these parallel robots. So, the robots will be controlled in a semi-automatic way when it displaces along the tubular or metallic structures.

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

### **How to reference**

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