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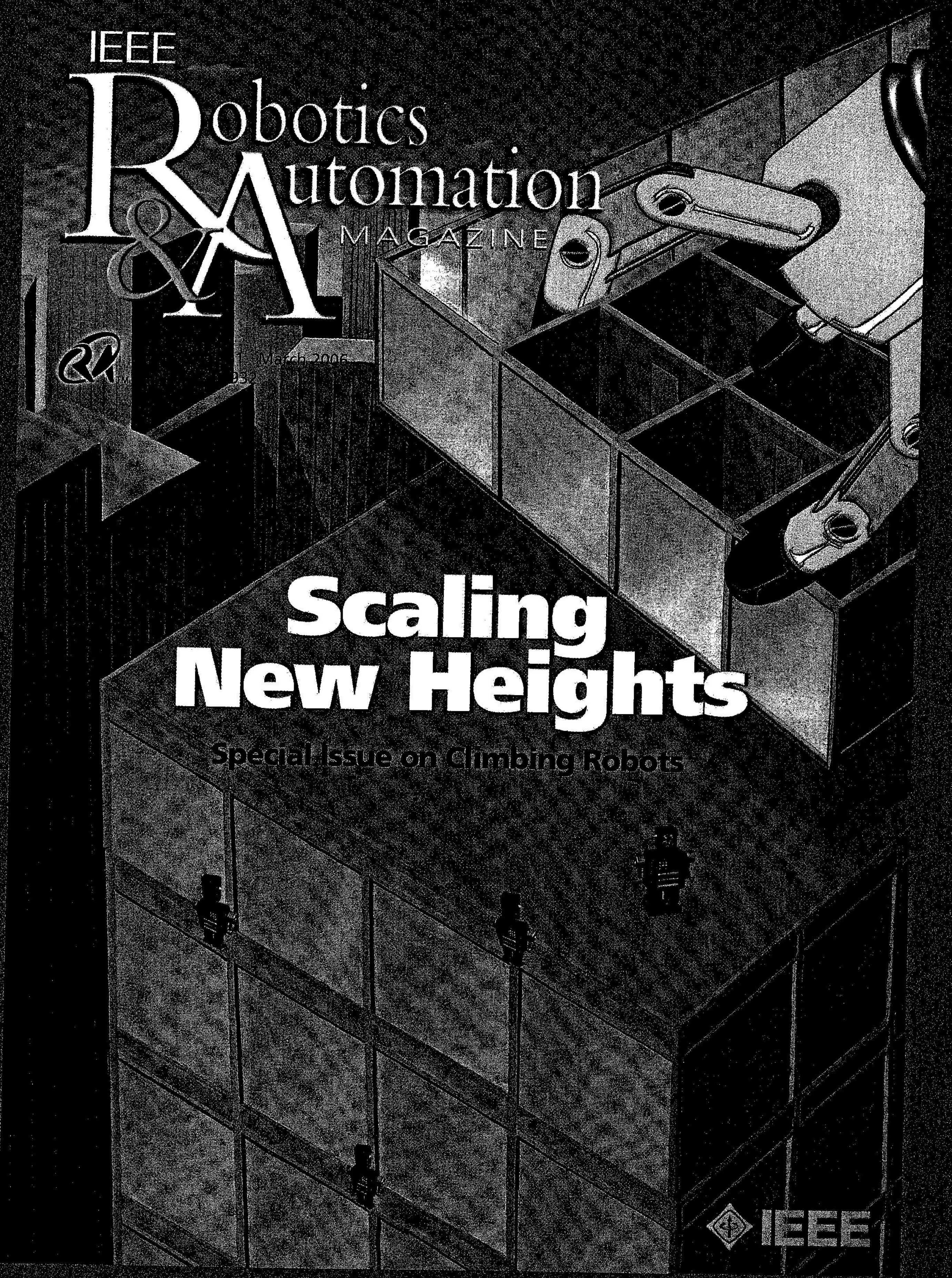

Scaling New Heights

Special Issue on Climbing Robots

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This special issue focuses on climbing robots—those robots that move in complex three-dimensional environments. Also in this issue are three other features, including one on the iRobot Roomba, and two new magazine departments "Practitioner's Corner" and "Tutorial."

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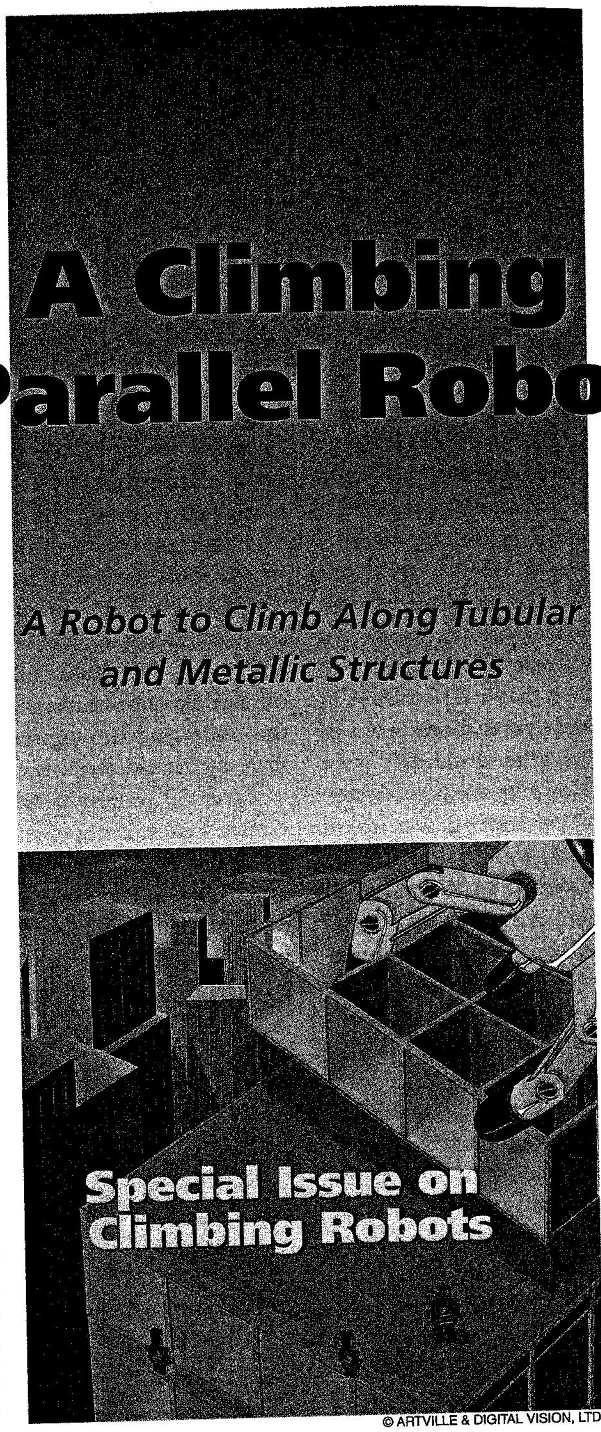
A Climbing Parallel Robot

A Robot to Climb Along Tubular and Metallic Structures



Although open-loop serial robots are extremely common in industry, parallel robots are becoming more popular in some industrial applications, medical fields, and services due to their good performance. These types of robots can be found in various applications where they have an advantage over serial robots. Parallel robots are used in the medical sector [1], in ophthalmic surgery, in endoscopic devices, and in the development of high-precision surgical instruments [2]. Parallel robots are also used for manipulating light materials in the food industry, such as in tasks with manipulation cycles of 0.4 s, speeds of 10 m/s, and accelerations of 10 G. This kind of dynamic performance is very difficult to obtain in serial robots. One of the most promising advances for the machining industry is the use of parallel robots in the development of new-generation computer numeric control (CNC) machining center tools [3]. The CNC machining center tools are based on a parallel mechanism that allows up to six degrees of freedom (6 DOF), which is impossible to obtain with a conventional tool.

Parallel robots based on Stewart-Gough's platform (S-G) are well known for their use in flight simulators [4] and other types of vehicle simulators to train civilian or military crew [5].

The evolution of parallel robots has not only been concentrated in industrial applications but also in less conventional but promising ways, such as the use of S-G for mobile robots to climb palm trees, get around, and move along the interior or exterior of tubular structures [6]. These robots can also climb metallic structures such as bridges or building domes.

Therefore, this article aims to inform the scientific community of the promising applications that can be obtained from parallel robots for climbing. We will explore the most important aspects of the mechanical design and control of climbing parallel robots (CPRs) based on the S-G platform for tasks in tubular or metallic structures.

Comparative Analysis Between CPR and Serial Robots

Before defining any difference between serial and parallel robots for climbing, a brief description of the features of these robots should be considered [7]:

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- An S-G parallel robot is a very simple machine that consists of two rings that are joined by six linear actuators through universal and spherical joints at every end. (Figure 1 shows a robot for climbing tubular structures.) To hold itself while climbing, the robot is equipped with a radial gripping device on every ring to hold firmly onto the tube. The climbing process is conducted by alternating the hold and release of each ring to enable displacement.
- Thanks to its linear actuators, a parallel robot has a high proportional ratio of payload and deadweight that is directly connected to its lower ring, which holds as the upper ring is displaced.
- An S-G parallel robot is sturdy due to the parallel configuration of its linear actuators, thereby creating a reticulated configuration.
- This type of robot has high speed and acceleration capacity thanks to its low weight inertia.

Parallel devices have clear and important differences in kinematics and dynamic behavior from climbing devices that use serial legs, which are formed by various links in series. The important differences are as follows:

- The effects of external forces cumulatively affect all elements of the mechanism in a serial robot. Therefore, the sum of the deadweight and inertia of the other links is concentrated in the link located next to the body of the robot.
- In contrast, the external forces that affect the end effectors are shared in parallel among the linear actuators in S-G parallel robots. Therefore, each linear actuator is affected less by the inertia of the other elements. It is also important to point out that the weight of every linear actuator has an effect solely on itself.
- The kinematics and dynamics design of an open-loop serial robot has been thoroughly studied, and diverse methods to resolve such problems are known. This is also why serial robots have been used for a long time and employed extensively in industry.
- S-G parallel robots are mechanically less complex than serial robots [8]. However, their kinematics and dynamics designs are more difficult to resolve [9]. In particular, a direct kinematics solution is difficult to derive due to multiple possible solutions that can be obtained for the same extension of the linear actuators. In practice, a numerical method to resolve the direct kinematics in real time is usually done.

As mentioned above, it is possible to consider the most important difference in the behavior between serial and parallel robots in accomplishing climbing tasks. The mean aspects to consider in climbing robots are:

- The robot must carry its weight and also its payload. In serial robots that use legs for climbing, force in the actuators next to the base of each leg is very high [10]. It therefore requires the mechanical design to be robust and heavy, necessitating powerful torque in the robot's actuators. Velocity is notably reduced in robots using legs for climbing. However, S-G parallel robots are very different because all six actuators move, sharing the weight and payload. Besides, the actuators that displace the robot are independent from its holding system, which is located in its rings as shown in Figure 1.
- In robots with legs for displacement along pipes, geometrical ability is limited when the robot has to rotate to accomplish tasks on the opposite face of the tube. This kind of action is very common for CPR, since it requires minimal turning steps. As a conclusion, climbing robots with legs, besides having limited dynamics and kinematics that complicate displacement for a given task, have no clear solution for the problems formerly mentioned, as they depend on the mechanical structure.

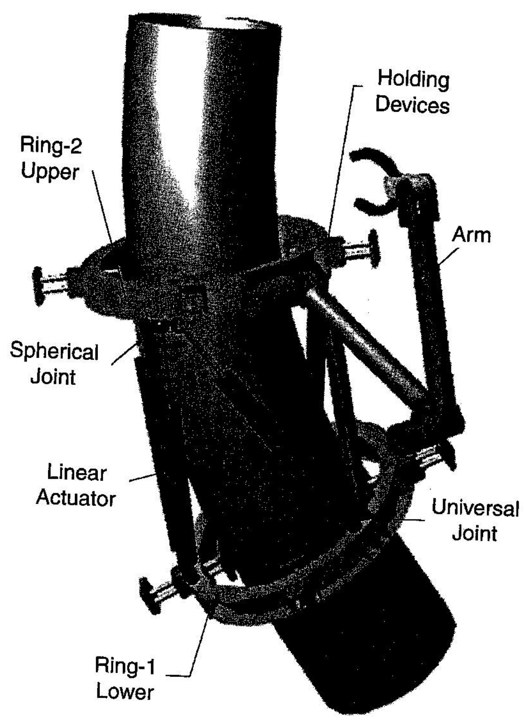

Figure 1. *S-G climbing parallel robot.*

The use of parallel robots for climbing different types of structures has been proposed after considering all the possibilities mentioned.

Parallel Robots for Climbing Tubular Structures

The use of the S-G platform for CPRs to perform tasks in tubular structures such as oil pipes, bridge steel cables, towers, and trunks of palm trees is very promising [6].

Mechanical adaptation is the first aspect to be solved in developing a CPR. As shown in Figure 2, it is necessary to divide the two rings into two parts connected by a hinge and a lock with a clamping device so that the S-G platform can adapt to climb outside the tube. This configuration allows the CPR to be assembled on the tubes as shown in Figure 1. It also allows the gripping system to be attached in every ring so as to hold out upon displacement inside the tube [6]. The gripping system for holding out is radial to the rings, as observed in Figure 2(a) and (c). Undoubtedly, the most important adaptation is redesigning the robot universal joints. It is necessary to design a special universal joint that is capable of large rotations, as observed in Figure 2(b). These joints should be more mechanically robust than standard universal joints.

Morphology of Robots for Climbing Tubes

CPRs can climb along the exterior and interior of tubes. These two possibilities in displacement are as follows:

1) Such displacement has already been mentioned in Figure 1. It consists of the robot holding around the tube and moving up by using grips attached to the rings. The CPR displaces along the tube as one ring holds up and the other free ring moves on. In a similar manner, CPRs can be used to climb inside tubular structures, as shown in Figure 2(c). This robot can move its rings along the curve of a tube through a system that controls the centering of the rings.
2) The other manner of climbing is shown in Figure 3. Two arms that can extend and retract are connected to each ring and serve as a holding device. Thanks to its structure, this type of robot works when climbing outside tubular structures with obstacles.

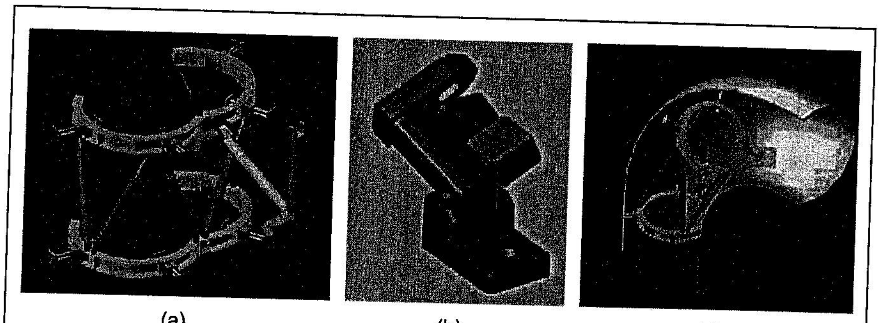

Figure 2. *Mechanical adaptations of an S-G platform: (a) CPRs for climbing the exterior of tubes; (b) an open universal joint; and (c) CPRs for climbing the interior of tubes.*

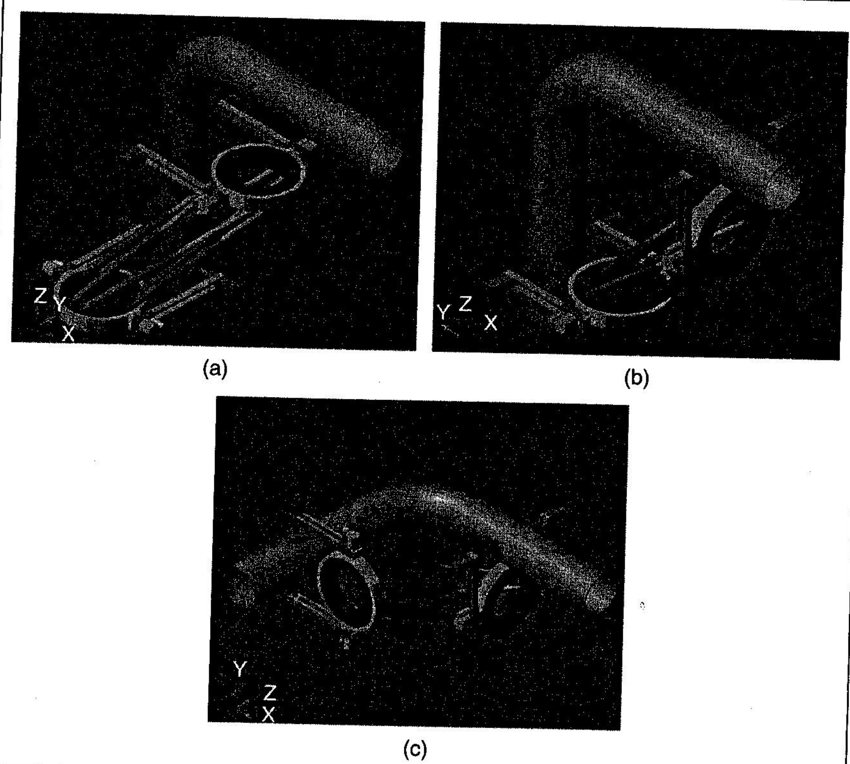

Figure 3. *A CPR robot climbing outside tubular structures.*

Development of a Pneumatic Robot for Climbing Palm Trees

A CPR prototype called TREPA has been developed to climb along trunks of palm trees with the objective of branch trimming and fumigation. Palm trees are very common on the Mediterranean coast and grow as high as 18–22 m. Currently, most palm trees on the Spanish Mediterranean coastlines are affected by disease. The problem is difficult to control as there is a lack of expert operators who can climb the palm trees to trim up the branches and spray insecticide. The automation of such a task is an excellent alternative due to the risks of falling from such height and becoming contaminated by the insecticide.

Algorithms for CPR in Tubular Structures

The automatic control of a robot that climbs along tubular structures should take into account geometrical changes in the path of the tubes. As a consequence, three 120° ultrasonic sensors have been installed in every ring of the TREPA robot. The three sensors enable the calculation of the difference between the center of the ring and the tube [6]. Based on this estimate, an algorithm to control the displacement of the moving ring can be created by keeping the ring centered and following the curve of the tube automatically [11]. In this context, the inverse and direct kinematics problems need to be solved as well to control the automatic climbing of a CPR along a pipe. A brief description of a climbing cycle, which explains the compromise between two solutions of kinematics, is shown as follows:

1) At the beginning of a climbing process, for example, the lower ring is held onto the tube by its clamping system, as shown in the sequence in Figure 4.

2) The actual configuration of the robot with respect to the reference system of the lower ring can be determined by means of the trajectory control algorithm, as shown in Figure 5 using the direct kinematics solution.
3) According to the actual configuration of the robot (with the system of reference in the lower ring), the total path of the center of the ring (upper ring) is calculated through the pipe line, and this path is divided into steps. Based on an inverse kinematics solution, displacement of each linear actuator is calculated; C_i = C_1, C_2, C_3, C_4, C_5, C_6). From the beginning of the cycle, and every time the upper ring passes through a step of the path, the centering of the ring is automatically corrected based on the measurements of the ultrasonic sensors. This action is conducted by the path control algorithm. Besides this correction, adjustment on the orientation of the ring is carried out by the algorithm.
4) While the upper ring is displaced, and before the ring moves forward to the next step, the validity of displacement is verified by an analysis of singularity through the robot Jacobian. In case of a singularity, the next movement is canceled. The mobile ring clamps up, and the new configuration is calculated through direct kinematics. While doing so, both rings are holding up.
5) Based on the calculated configuration of the robot as previously mentioned, the reference frames of the rings are interchanged. The CPR takes the upper ring as a new system of reference and goes back to Step 1 to pull up the lower ring.

An inverse kinematics solution is calculated from the position and orientation of the final effectors to get the necessary command variables required for a programmed path planning. The inverse geometric model of the platform implies establishing the values of the joint values of the kinematic chain for a certain configuration of the final effector. A solution can be obtained from the next vector description on generalized coordinates

$$r_{ABi} = r_1 + A_1 s_1^{\prime Bi} - s_0^{Ai} \qquad i = 1, \ldots 6,$$

where s_0^{Ai} y $s_1^{\prime Bi}$ are position vectors that locate universal and spherical joints A_i and B_i with respect to the base reference frame and mobile ring coordinate system, respectively. The r_{ABi} vectors are the joint variables calculated from the inverse solution, whose magnitude C_i gives the required configuration of the linear actuators.

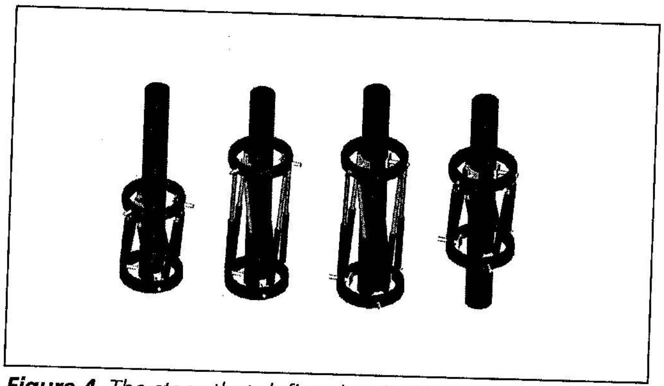

Figure 4. *The steps that define the climbing process of a CPR.*

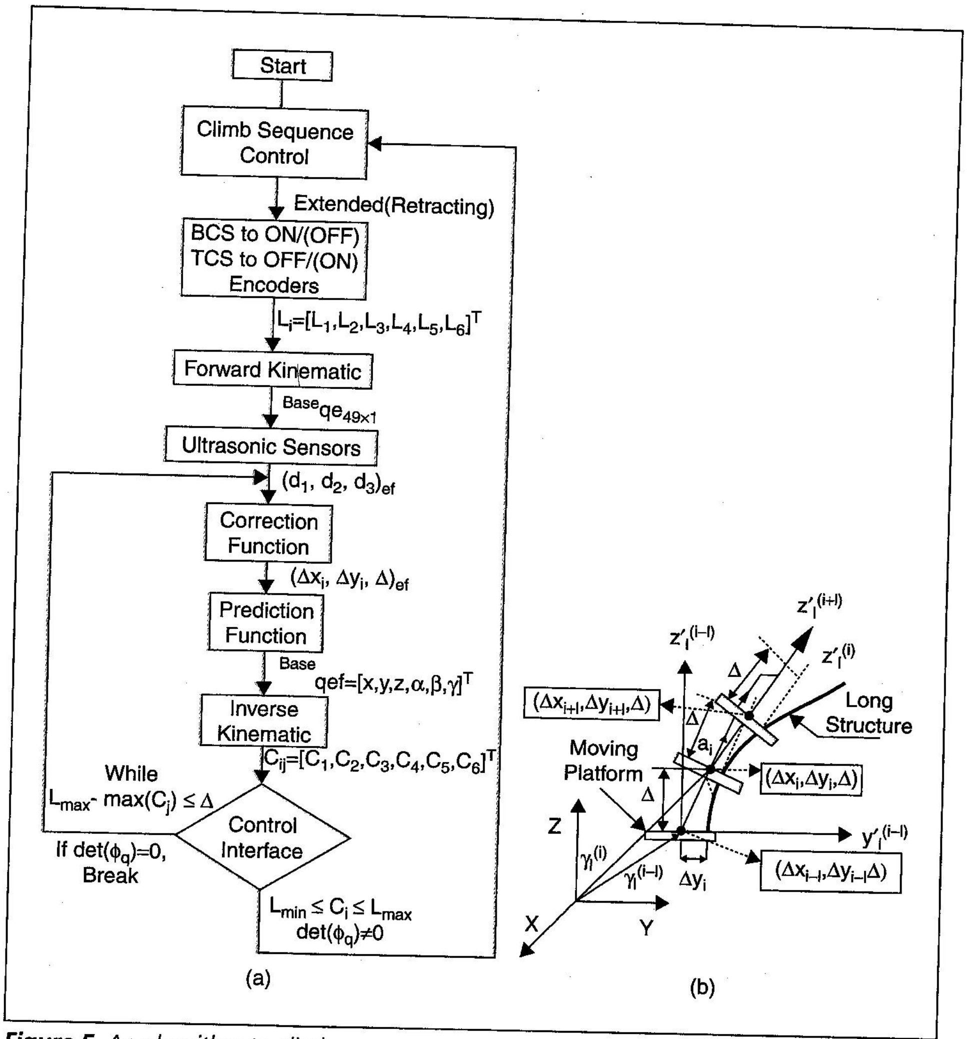

Figure 5. *An algorithm to climb up.*

Figure 6 shows a sequence of images of the TREPA robot prototype. It has six 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 multiaxis Delta Tau PMC-VME card has been used for the control structure of the robot.

In Figure 6, the parallel robot is shown climbing on a palm trunk. The images show the robot in different positions of the palm trunk. The first version of the prototype designed to climb this type of structure moves at a velocity of 0.4 m/s.

Parallel Robots for Climbing Metallic Structures

Usually, metallic frame structures have inner installations, such as electrical, plumbing, or fire installations, that require maintenance. Structures such as metal bridges, or industrial structures such as nuclear plants, require maintenance as well.

The most common task for actual climbing robots is, possibly, structural defect inspection of bridges and other surfaces. Nevertheless, the future brings up new challenges for robots, among them underwater inspection and mechanical tasks that require the management of metal sawing and welding tools. Teleoperated robotic tasks for cleaning ship hulls are also being intensively studied for several labs throughout the world. Thus, it is necessary to consider that CPRs should include interfaces for all the tasks described above in addition to the dismantling of nuclear plants or maintenance of oil rigs.

A parallel robot with proper mechanical adaptations, as shown in Figure 7, is one of the best options for performing tasks in metallic frame structures. Mechanical modifications are explained as follows:

- An external rotating ring is assembled on each ring of the parallel robot (this external ring is able to rotate ±90°). This external ring must have two extendable arms to clamp the robot to the structure. These arms

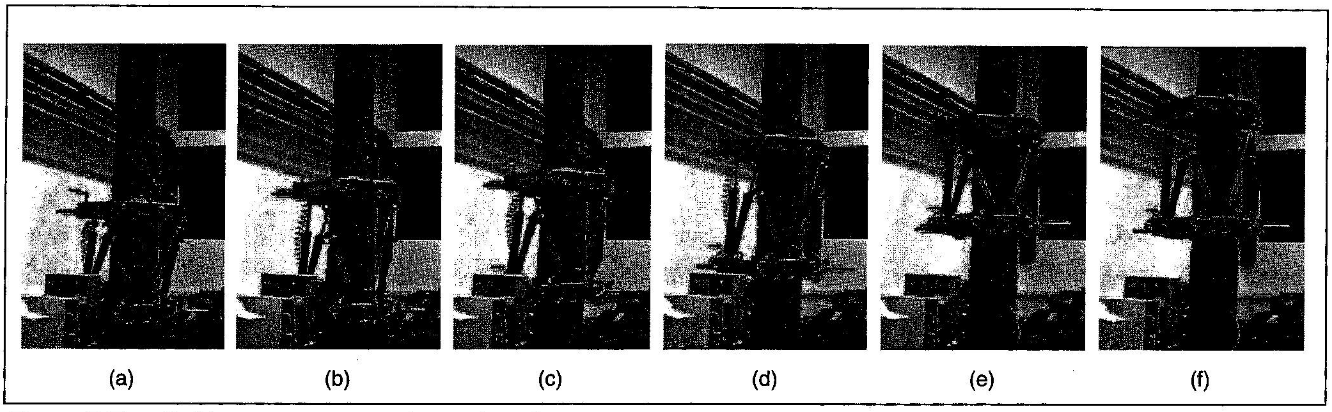

Figure 6. *The climbing sequence experimental results.*

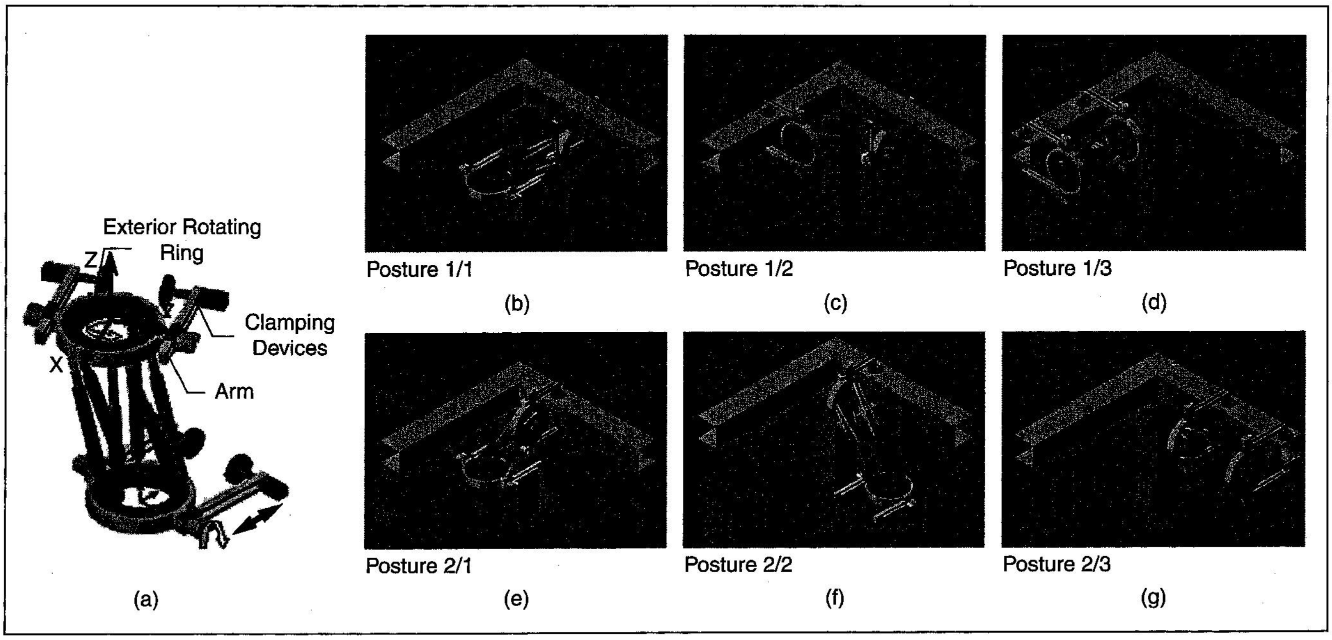

Figure 7. *(a) CPR robot for metallic structures and (b)–(g) examples of a climbing sequence in a structural frame.*

must be articulated in order to rotate on the joint that is connected to the external rotating ring. These arms should also be retractable to avoid possible risk of collision with the beams of the frame structure.

A basic problem that must be solved in the development of climbing robots for structural frames is that the robot must be able to get around structural nodes. Figure 7 shows some sequences that solve these problems; these sequences may be followed so that a CPR robot can get around a structural node.

Sequences of Climbing in a Structural Metallic Frame

In order to climb along a metallic structure, a CPR needs to follow a sequence of postures, as shown in Figure 7.

In order to climb, a CPR should have an exterior rotating ring on every base ring available to be assembled or not. For example, Posture 2/2 in Figure 7 shows an exterior rotating ring assembled in each of the CPR's rings. Thanks to the configuration mentioned above, it is possible to increase the quantity of available postures to get around a structural node.

Sequence 1 shows that to pass a structural node, Postures 1, 2, and 3 are required. However, the robot's closeness to the structural node shows some problems for the next displacement of the robot. Therefore, some intermediate postures are considered to get around this problem.

Development of an Experimental Robot for Climbing Structures

An experimental prototype has been developed as shown in Figure 8. This CPR prototype has been created without exterior rotating rings. As previously mentioned, exterior rotating rings are not required to get around a structural node; however, they do give the robot greater geometrical ability to move around. This simplification reduces the complexity in developing the prototype.

The objective in this experimental phase has been to study the kinematics behavior of the CPR in the postures detailed below. Some universal joints should be considered when the configuration is close to its limits of rotation. Thanks to the robot's mechanical design, universal joints have a wide turn angle that allows the upper ring to be perpendicular to the lower ring.

Results

Some sequences that combine the postures of Figure 8 are feasible steps to get around a structural node. The experimental results show that the completion of such sequences is possible.

To obtain such postures, it is necessary to conquer some basic problems.

- First, one is required to come up with an appropriate design in the universal joints. These joints must be open to allow broad angles for rotating.
- Second, four postures shown in Figure 8 can be reached by the upper ring. As observed, the postures can be reached even when the upper ring is near its singular behavior of orientation.

Conclusions

The S-G platform with proper mechanical adaptation could be used for a CPR robot. A CPR has great advantages compared to a serial robot with legs. Advantages, such as high

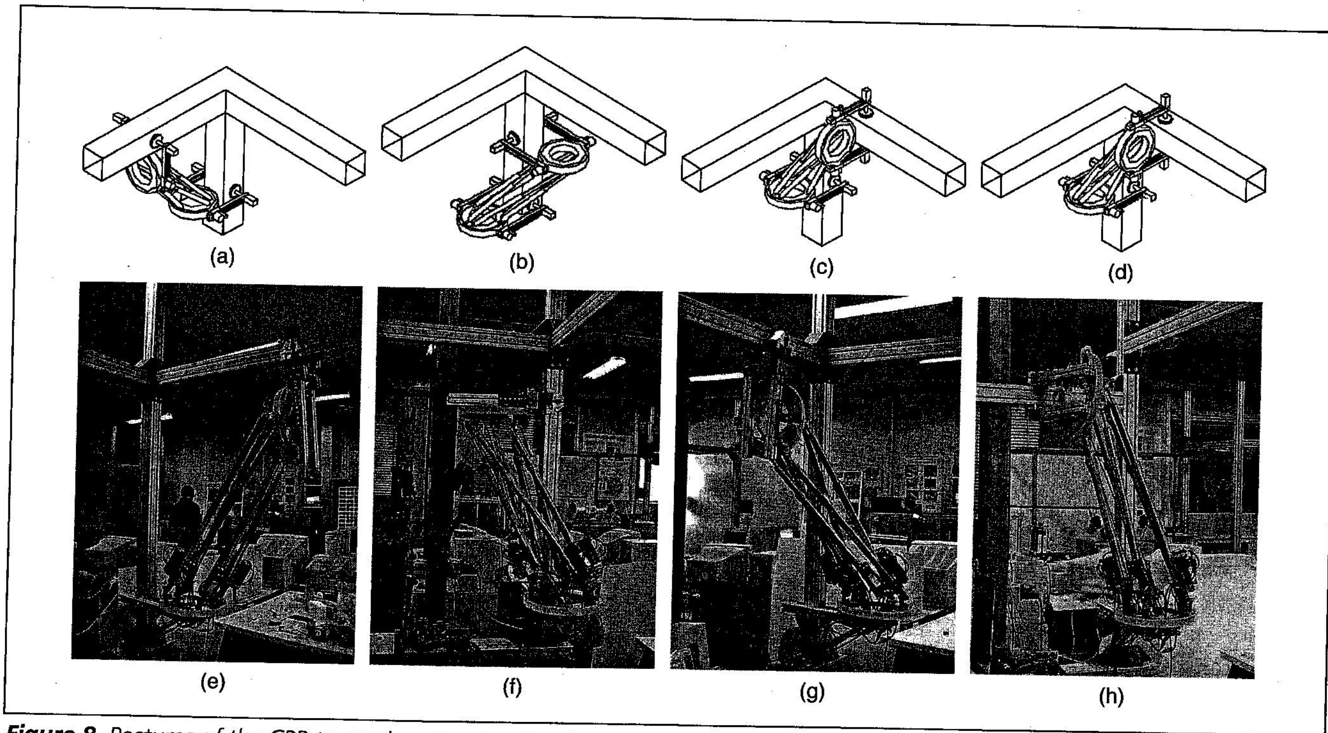

Figure 8. *Postures of the CPR to evade a structural node.*

weight payload capacity, are obtainable since the final effectors of the robot are directly connected in parallel to the base through the linear actuators. Consequently, a heavy weight load capacity is essential for a climbing robot, as it must consider carrying its deadweight as well.

Weight restriction slows down advancement in the development of climbing robots.

The results obtained are quite promising in many ways.

- First, a parallel robot mechanism is simple and robust. Its deadweight is less than that of a serial robot designed to perform similar tasks.
- The simplicity of the parallel robot's mechanical design is excellent, as it has two rings connected by six linear actuators though universal and spherical joints.

The CPR has overcome two main difficulties. The first is related to the task of climbing along tubes or trees. The development of the experimental prototype and the results show that the parallel robot is able to climb along tubes and stems. This capability is highly regarded when the parallel robot is able to adapt to the structural changes and get around to perform its task. The second difficulty is related to climbing structures. The design of climbing robots for structures has 6 DOF; it allows one of the two rings to orient and displace conveniently and hold onto the rails of the metallic structure.

To overcome the structural node, the robot must complete some postures that are relatively simple compared to other types of climbing devices. Some problems of singularity in certain orientations inside the working space of the robot can arise. But, on the whole, the climbing sequences and four postures previously mentioned are attainable.

In conclusion, CPRs have great advantages that make them more promising than other climbing robots. Some research work in the teleoperation for these devices is being done, along with development of algorithms that will operate the robots semiautomatically in their trajectory when they displace along the tubular or metallic structure.

Acknowledgments

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Keywords

Parallel robots, service robots, climbing robots.

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