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PARALLEL CLIMBING ROBOTS FOR CONSTRUCTION, INSPECTION AND MAINTENANCE

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Abstract: In this paper we propose the use of parallel platforms as climbing robots considering the big load capacity that this structures have and their ability to progress on the workspace. In the first part we suggest a theoretical framework where dynamics and kinematics relationships that characterize these robotics structures are defined for their applications as climbing robots. Furthermore we propose several mechanical architectures for parallel climbing robots, like robots for bridge or building structures. Finally we describe a parallel robot architecture that nowadays is being developed for the maintenance of post, cables or palm trees.

Keywords: Robotics, climbing robots, construction robots, parallel robots, field robotics.

1 INTRODUCTION

Typically, walking and climbing robots base their displacement on the movement of their legs [2], [5]. In most of the mentioned robots, legs are made of serial-connected articulated links. It is remarkable that the use of legs on climbing robots implies a great number of degrees of freedom, with motors and sensors for each one of them, increasing the complexity of control, the machine weight and cost.

On climbing robots, availability of a great number of redundant degrees of freedom does not necessarily increase the ability of the machine to progress on the workspace. An important number of the degrees of freedom of a climbing robot stay hold to be used as a base to the body and as reference for the legs that at this moment are operating as an advance mechanism. Architecture of serial legs also implies a limit on load charge, what is a typical effect on serial articulated mechanisms influenced by force and torque effects that are present on joints and so that on the capacity of power actuators [5].

In base on these considerations, it is also noticeable that relations weight/power on climbing robots are high and the useful load capacity of these mechanisms and their velocity are limited.

To summarize, technical characteristics of climbing robots with legs that implies limits suitable for improvement are:

- Use of a great number of DOF, with few of them on movement and working in a combined way.
- Limited use of the DOF and of the available total power.
- High weight, that limits the relation weight/power and the velocity of robot.
- Limited capacity for using with heavy loads.
- Avoid power actuators as structural elements.

To solve some of the preceding problems, this paper suggest some mechanical structures based on parallel platforms with 6 degrees of freedom.

Parallel platforms present the next advantages that made them especially suitable to work as climbing robots:

- Power actuators are connected directly to the base of robot, what is the final effector. Due to that, the power actuators are used as structural elements and they work simultaneously, that implies the capacity of manipulating higher loads than their own weight.
- Parallel structures are mechanisms that offer a high stiffness, with low weight and high operating velocity, compared with any other kind of robotic structure.
- To define one's position and to point itself inside the workspace, parallel structures need 6 DOF. Using all the degrees of freedom for the displacement, the proposed climbing robots use a minimum number of power actuators, comparing with other kind of climbing robots.

2 THEORETICAL FRAME FOR RRP̲S PARALLEL PLATFORMS

The type of robots proposed in this paper are based on a parallel platform with 6 degrees of freedom [7], with a **RRP̲S** kinematic chain (where the **RR** degrees of freedom belongs to an universal joint, **P̲** is a prismatic degree of freedom that belongs to the linear power actuator and **S** is the spherical joint connecting the linear actuator with the final effector).

2.1 Inverse kinematic solution of a RRP̲S platform.

The inverse kinematic solution that is calculated from the position and orientation of the final effector allow us to get the necessary command variables to fit with a programmed path planning.

The inverse geometric model of a RRP̲S platform implies establishing the values of the joint variables of the kinematic chain for a certain configuration of the final effector. The raising of the solution can be easily obtained from the next vectorial description on generalized coordinates.

$$r_{ABi} = r + Acs_i' - s0 \qquad (1)$$

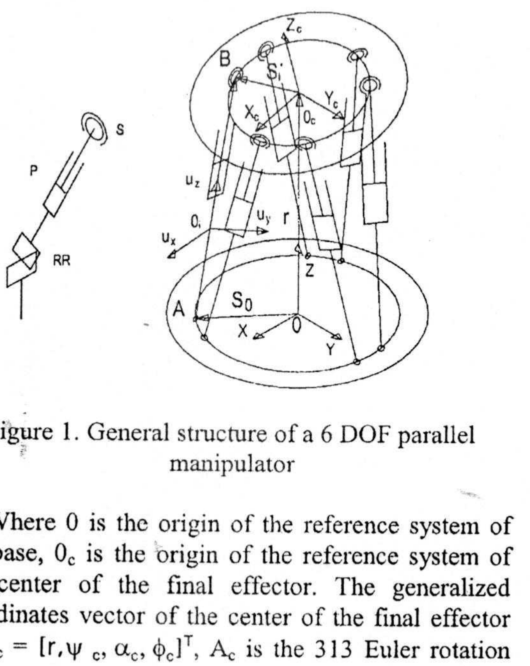

Figure 1. General structure of a 6 DOF parallel manipulator

Where 0 is the origin of the reference system of the base, 0_c is the origin of the reference system of the center of the final effector. The generalized coordinates vector of the center of the final effector is: $q_c = [r, \psi_c, \alpha_c, \phi_c]^T$, A_c is the 313 Euler rotation matrix, s_i and s_0, are vectors relatives to the system 0_c y 0 respectively. The r_{ABi} vectors are the joint variables that are calculated from the inverse solution, whose magnitude gives the configuration of the linear power actuators.

Based on the r_{ABi} vector norm, it is possible to determine the angles ψ_i, α_i, ϕ_i of the generalized coordinates vector $q_i = [\, r_{ABi}, \psi_i, \alpha_i, \phi_i \,]^T$. For this purpose a reference system 0_i with the u_z axis aligned along the unitary vector of the r_{ABi} is fixed, as it is illustrated on figure 1, so that:

$$u_z = \frac{r_{ABi}}{\left\| r_{ABi} \right\|}, \quad u_x = \frac{u_z \times S_0}{\left\| u_z \times S_0 \right\|}, \text{ and } \quad u_y = u_z \times u_x$$

From these unitary vectors, the matrix of director cosines can be obtained $A_i = [\, u_x, u_y, u_z \,]$ and so the angles ψ_i, α_i, ϕ_i, or the Euler parameters: $P=[e^i_0, e^i_1, e^i_2, e^i_3\,]$ for the matrix $A_i = \left(2e_0^2 - 1\right)I + 2\left(ee^T + e_0\tilde{e}\right)$ can be determined.

2.2 Numerical model for the direct kinematic solution.

The direct kinematics of a **RRP̲S** platform study the relationships between the command variables of the linear actuators and the resultant position of the final effector.

In specialized literature there are several methods for the geometrical calculation of direct kinematic of 6 DOF parallel platforms. Some of them allow us to get the possible solutions through the use of polynomials that result of the geometric modeling of the kinematic chains of the platform. For example in [6], the 16 possible solutions for a 6 DOF platform are calculated; [4] and [1] proved that the Stewart platform have 12 possible solutions; [7] suggested a systematic method to obtain the minimal polynomial equations for certain cases of parallel platforms, like for example a 3 DOF. With this last method a solution of polynomial of 8 degrees can be obtained, although for a general 6 DOF robot, the Nair's method arrives to polynomials of 144 degrees.

In this section, a numerical method based on the initial estimation of the generalized coordinates vector q_i will be exposed. In general, a 6 DOF RRP̲S parallel platform is formed by 12 links that constitute the linear actuators. Each couple of the previous links, are linked between them by a prismatic joint, and each one of the extremes are connected to the base and to the final effector through a spherical joint and an universal joint. Then the generalized coordinates vector will be represented as: $q=[q_1, q_2, q_3, \ldots, q_{13}]^T_{91x1}$. Where q_1 is the generalized coordinates system of the final effector and $q_2, q_3, \ldots, q_{13}$ correspond to the unit of generalized coordinates assigned to the couple of links that form the linear actuators. In general, each link is defined by a generalized coordinates system where: $q_i=[r_{ABi}, P_i]^T$ with $r_{ABi} = [x_i, y_i, z_i]$ and the Euler parameters: $P=[e^i_0, e^i_1, e^i_2, e^i_3\,]$.

The description of the kinematic chain of a RRP̲S, is based on the constraints vector:

$$\phi(q,t)=\begin{bmatrix}\phi^{k}(q)\\ \phi^{D}(q,t)\\ \phi^{P}(q)\end{bmatrix}_{91x1}=0 \qquad (2)$$

Where $\phi^{k}(q)_{72x1}=0$ is the vector of the 72 holonomic constraints imposed by the prismatic, spherical and universal joints. $\phi^{D}(q,t)_{6x1}=0$ is a vector of 6 constraints imposed by the actuators, that in this case they are function of the command joint variables for which direct kinematics will be calculated. $\phi^{P}(q)_{13x1}$ is a vector of 13 constraints for the normalization of the Euler parameters.

Spherical Constraint

Spherical constraint restricts 3 degrees of freedom, so that they can be described as it is shown in Figure 2 and in the following equation:

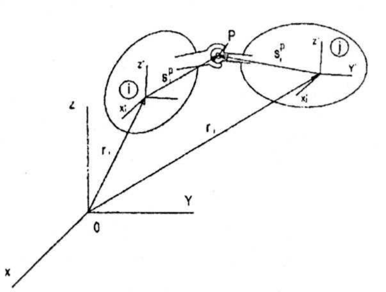

Figure 2. Spherical constraints

$$\phi^{(s,3)}(p_i,p_j)_{3x1} = r_j + A_j s_j'^{P} - r_i - A_i s_i'^{P} = 0 \quad (3)$$

This type of constraint is defined describing a common point 'p' of the spherical joint from the coordinates system x'_i, y'_i, z'_i and x'_j, y'_j, z'_j of bodies i, j.

Universal constraint

The universal constraint is shown in figure 3. This type of constraint restricts 4 degrees of freedom, so that their description is based on the combination of a spherical constraint and the dot product of the unitary orthogonal vectors h_i and h_j, (with h_i=$A_i h'_i$), then: x'_i, y'_i, z'_i

$$\phi^{s}(p_i,p_j)_{3x1}=0 \qquad (4)$$

$$\phi^{(d,1)}(h_i,h_j)_{1x1}=h_i^{T}h_j= h_i'^{T}A_i^{T}A_j h_j'=0 \quad (5)$$

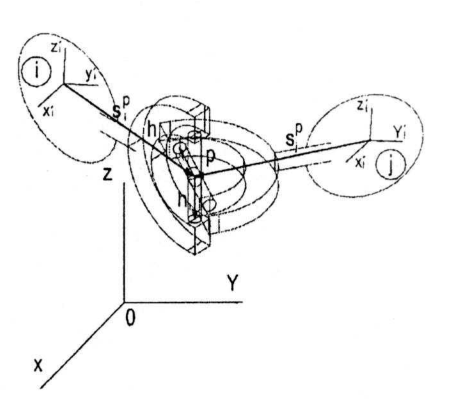

Figure 3. Universal constraints

Translational constraint

The translational restriction is used to describe the prismatic joints of the linear actuators. The description of this constraint is based on the vector products of vectors h_i, h_j and d_{ij}, and the dot product of the unitary orthogonal vectors f_i and f_j.

$$\phi^{(p,2)}(h_i,h_j)_{2x1}=\begin{bmatrix}\phi^{d1}(f_i,hj)\\ \phi^{d1}(g_i,hj)\end{bmatrix}=0 \quad (6)$$

$$\phi^{(p,2)}(h_i,d_{ij})_{2x1}=\begin{bmatrix}\phi^{d1}(f_i,d_{ij})\\ \phi^{d1}(g_i,d_{ij})\end{bmatrix}=0 \quad (7)$$

$$\phi^{(d,1)}(f_i,f_j)_{1x1}=f_i'^{T}A_i^{T}A_j f_j'=0 \ (8)$$

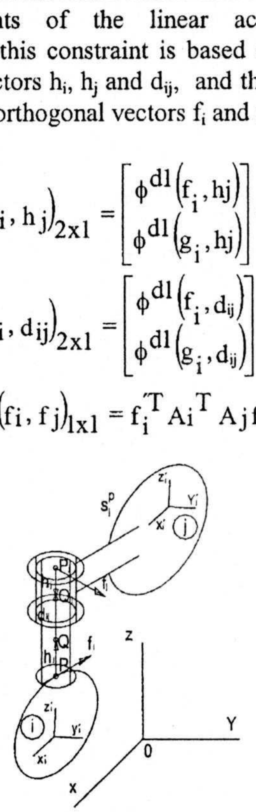

Figure 4. Translational constraint

Constraints of the normalization of the Euler parameters

The description of the multibody reference system in terms of Euler parameters force us to establish constraints for the normalization of these parameters, and they are written as:

$$\phi_i^{P}=p_i^{T}p_i-1=0 \qquad (9)$$

The constraints of actuation $\phi^{D}(q,t)_{6x1}=0$ are used to obtain the direct kinematic solution of a RRPS platform.

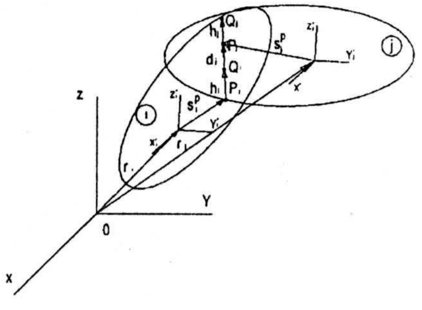

Figure 5. Relative translational constraints of a linear actuator

According to Figure 5 bodies i,j form the linear actuator with a translational joint that is described through the points P_i, and P_j, the unitary vectors h_i and h_j are built between the couples of points P and Q. The constraint of the translational actuator can be written as the dot product of two co-linear vectors (if the vector $d_{ij} \neq 0$) minus a $C_{ij}(t)$ function that represents the displacement of the linear actuator which direct solution is being calculated.

$$\phi^{D}=\left(h_i, d_{ij}\right)_{1x1}=h_i^{T} d_{ij} - C_{ij}(t) \tag{10}$$

The unitary vector h_i can be written as: $h_i^T = h_i'^T A_i^T$ and $d_{ij}=r_j+A_j s_j'^P - r_i - A_i s_i'^P$, where vectors with inverted comma are referred to the systems i and j fix together to each body, as it is shown in Figure 5, where A_i and A_j are the rotation matrices in terms of the director cosines of each system.

Numerical calculation of the kinematic solution

As it was mentioned before, to calculate the direct kinematic solution we start from an approximated generalized coordinates vector q_i, and the displacement values $C_{ij}(t)$ (for the case of the direct kinematic solution it depends only on the command variable). For these effects, it is commonly used the Newton-Raphson method.

$$\phi_q \Delta q^{(j)} = -\phi\left(q^{(j)}, t\right) \tag{11}$$

$$q^{j+1} = q^{(j)} + \Delta q^{(j)} \tag{12}$$

where ϕ_q is the Jacobian of the vector of constraints described in (2) and $q^{(j+1)}$ is the direct kinematic solution when $\Delta q^{(j)} \approx 0$.

The computational model for the multibody inverse and direct kinematics has been implemented in Matlab. In the next figure, we present some results of simulations for a path planing based in a displacement of 800 mm (partitioned in 11 parts) of the climbing robot.

To suggest a idea of the computational cost of this simulation, we present a graphic relation that show the number of float point operations (Flops). In all cases we obtained an unique direct kinematic solution.

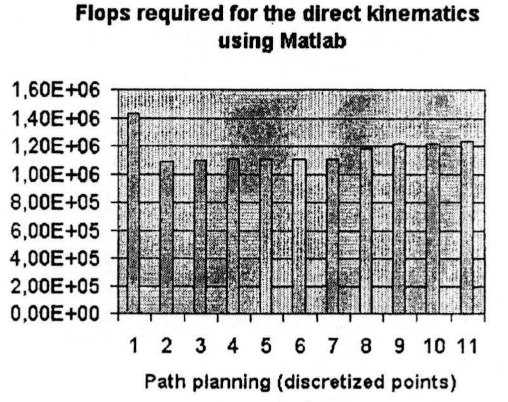

Figure 6 Multibody direct kinematics flops for a parallel climbing robot simulate with Matlab

23 Dynamic multibody of a RRPS platforms

The dynamic of a RRPS platform can be modelled and numerically calculated from next matricial differential-algebraic equation (DAE) as it is shown in [3]. Due to velocities and accelerations are not integrable, general expressions of dynamic, for the solution of the direct dynamic problem, must be written in terms of Euler parameters.

$$\begin{bmatrix} M & 0 & \phi_r^T \\ 0 & J' & \phi_{\pi'}^T \\ \phi_r & \phi_{\pi'} & 0 \end{bmatrix} \begin{bmatrix} \ddot{r} \\ \dot{\omega}' \\ \lambda \end{bmatrix} = \begin{bmatrix} F^A \\ n'^A - \tilde{\omega}' J \omega' \\ \gamma \end{bmatrix} \tag{19}$$

Where: J' y M are the inertia and mass matrices for each one of the nb bodies of the system, G_{3x4} are matrices that were obtained from the identities of the Euler parameters, $\phi_{\pi'}$ and ϕ_r are sub-matrices of the jacobian, $\ddot{r}$, $\dot{\omega}'$ are vectors of the linear and angular acceleration of the generalized coordinates systems q_i, F^A are the applied external forces, γ are the terms of the accelerations and λ are the vectors of the Lagrangian multipliers, that physically represent the constraints forces between the couples of bodies. The solution of the direct problem is complex. For this effect, the previous differential-algebraic equation must be solved considering the initial conditions, finding the accelerations and applying special numerical integration algorithms for this type of differential-algebraic mixed equations, with the purpose of obtaining the velocity and position that must also satisfy the next constraint equations

$$\phi(r,p,t)=0\,,\ \phi^{P}=0\ \text{y}\ \phi_{r}\dot{r}+\phi_{\pi'}\omega'=0\,. \qquad (20)$$

There are in literature several numerical integration methods, specially indicated for the solution of differential algebraic mixed equations, like the Coordinates Partition method [10], the Constraint Stabilization method, or the Hybrid Algorithms method [8], that combines the two preceding.

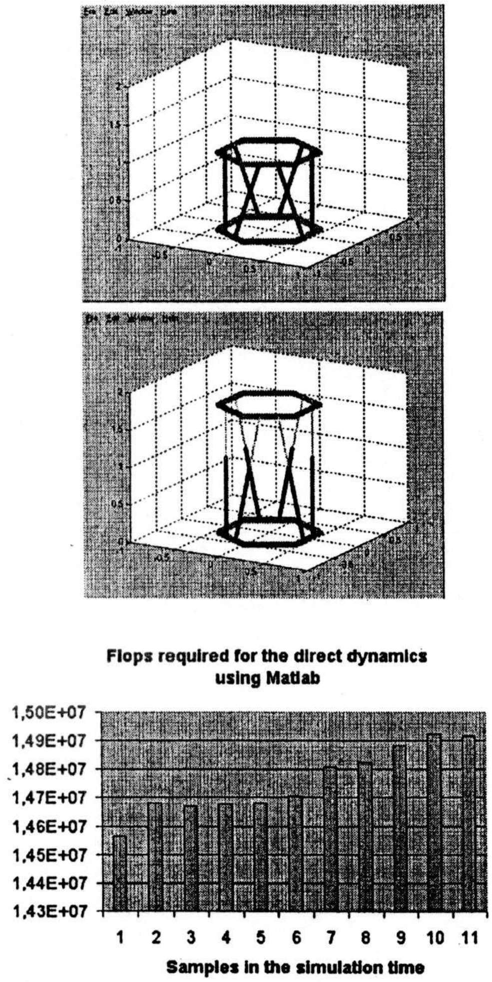

Figure 7. Animation and flops for the direct dynamics of a parallel climbing robot.

For the direct dynamics we developed a computational simulator in Matlab, based in the multybody dynamics. The figure-7, shows an animation of the model obtained for a constant force applied in each actuator during a period of 0.5 seconds. To solve the integration problem we used the Hybrid Algorithm Method [8].

3. MECHANICAL ARCHITECTURES FOR PARALLEL CLIMBING ROBOTS

The studied mechanical architectures that are presented in this paper, are relationed with parallel robots that can move through metallic structures, front of buildings, inside tubes and climb through posts or cables.

3.1 Climbing robots for displacing over structural frames

Next figures show different kinematics configurations for parallel climbing robots that can manoeuvre over metallic structures of bridges or buildings. In all cases, mechanical architectures are based on RRPS platforms, made of a couple of rings linked between them by linear power actuators.

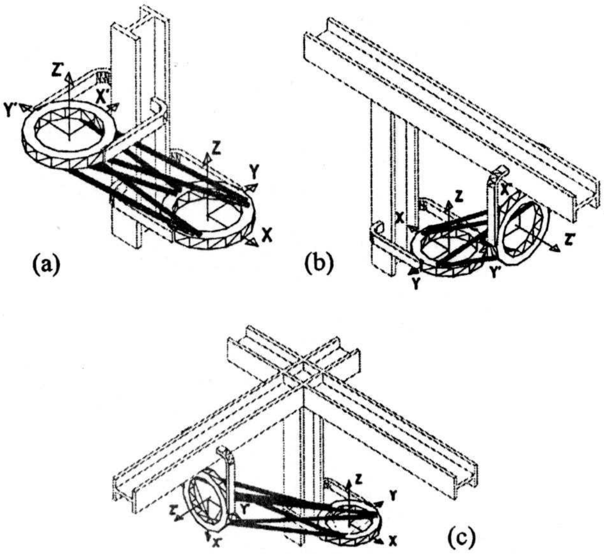

Figure 8. Three images showing the manoeuvre of a parallel robot over a structural frame. At the (c) configuration, an interference appears between the intermediate linear power actuator.

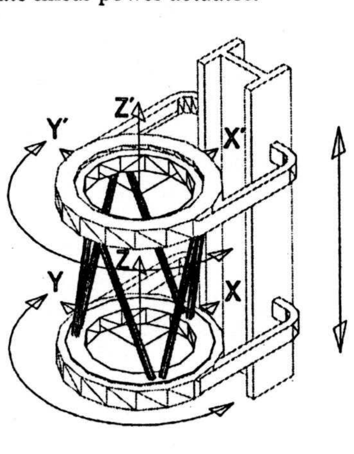

Figure 9. Parallel climbing robot proposed.

Figure 9, shows the suggested solution for the parallel platforms that should manoeuvre over bridges or building structures. Take note that an additional degree of freedom on each ring has been additioned, with the purpose of solving the interference problems between the linear actuators that can appear in determined configurations. From the point of view of control, teleoperation of this robots based on a parallel master robot will allow us to solve directly complex problems that the direct kinematic solution creates, the singularities and the reachable spaces inside the universe of work of the robot.

3.2 Climbing robots for building fronts and surfaces

For this applications, it can be deduced that a 6 DOF parallel architecture , as one's shown in Figure 8 (a) is perfectly possible. In general, applications in these cases are numerous, and go from the cleaning of fronts, welding inspection of boats, etc. Remembering that this type of robots has a great load capacity, it is not difficult to foresee that they can carry heavy welding systems. At each specific case, subjection legs and handler arms for the tool, must be adapted to the basic platform, as shown in the next section.

3.3 Climbing robots for posts, pipes and cables.

The maintenance of posts, pipes, cables and large cylindrical structures with regular or irregular sections (like palm trees) in general require robots capable of climbing and orientating itself on the workspace, with the goal of being capable of adapting to curvature variations that this type of structures present.

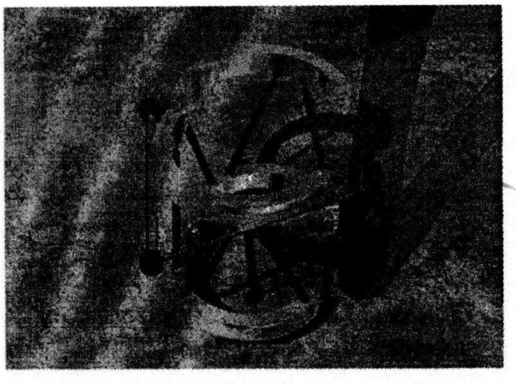

Figure 10. Architecture for a parallel climbing robot with a manipulator hand for large structures.

4. CONCLUSIONS

On this paper, we have presented an advance in the investigations nowadays taking place at the "Industrial Technology" group of this University, for the development of parallel climbing robots dedicated to the maintenance of large structures like posts or cables. Applications of these robots to the maintenance of bridges or building structures have also been studied. For the study of the kinematics and dynamics of this type of platforms, computational object oriented tools in C++ have been developed in Saltarén [9], using the multibody dynamics methods. With this developments we hope to solve numerically the complex problems of the direct kinematic and dynamics solutions, complete the necessary scene for the remote teleoperation of this machines, and validate control strategies too. Nowadays a prototype including a teleoperation system is being developed.

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