ABCM Symposium Series in Mechatronics - Vol. 2 - pp.190-195
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A NEW FAMILY OF 3-DOF PARALLEL ROBOT MANIPULATORS FOR PICK-AND-PLACE OPERATIONS

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Abstract. *In the past recent years, parallel kinematic structures have attracted a lot of attention from academic and industrial communities due to their potential applications not only as robot manipulators but also as machine tools. In general, they demonstrate higher performance than serial mechanisms, once parallel mechanisms are much more rigid, accurate and have higher load capacity and, therefore, can be lighter. This work introduces a new family of 3-dof parallel robot manipulator for pick-and-place operations. Its feasible topologies are described in accordance with possible forms of actuation. Important issues such as the position kinematics and workspace evaluation regarding the motion range allowed by installed actuators and joints are analysed.*

Keywords*: robot manipulators, topology, parallel kinematics*

1. Introduction

Most of commercially available industrial robots are based on serial kinematic structures, i.e., their actuators and moving links are assembled serially, one after the other, resulting only one open-loop kinematic chain to position and orient a gripper or welding electrode. During this last decade, both academic and industrial communities have demonstrated a research interest on using another kind of kinematic structure, known as parallel, which is characterized by the presence of many independent limbs (kinematic chains), actuating in-parallel or simultaneously on end-effector. This nonconventional architecture becomes attractive due to some potential advantages over its traditional serial counterpart. Among them, one can mention: high rigidity, lightness, fast dynamic response, precision and high load capacity.

Different types of parallel architectures have been proposed for pick-and-place operations. The Neos Tricept (Neumann, 1988) represents a tetrapod structure that contains one central passive limb to constrain the spatial end-effector's motion. Clavel (1990) conceived the Delta robot, a 4-dof parallel mechanism based on pantograph linkages. The H4 robot (Pierrot, 1998) has a similar architecture of Delta but employs topologically symetrical limbs. Tsai (1999) modified the Delta robot by replacing the spherical joints by using universal joints with special relative orientation of their rotating axis, in order to constrain the end-effector's motion to only three translations. More recently, novel 3-dof architectures such as the Universal Cartesian Robot (Kim and Tsai, 2002), Tripteron (Gosselin et al., 2004) and *3 $\underline{P}$CC* (Di Gregorio and Parenti-Castelli, 2004) present some convenient features: their set of nonlinear position equations become linear and fully decoupled which is not only valid for the inverse but also for the direct kinematics.

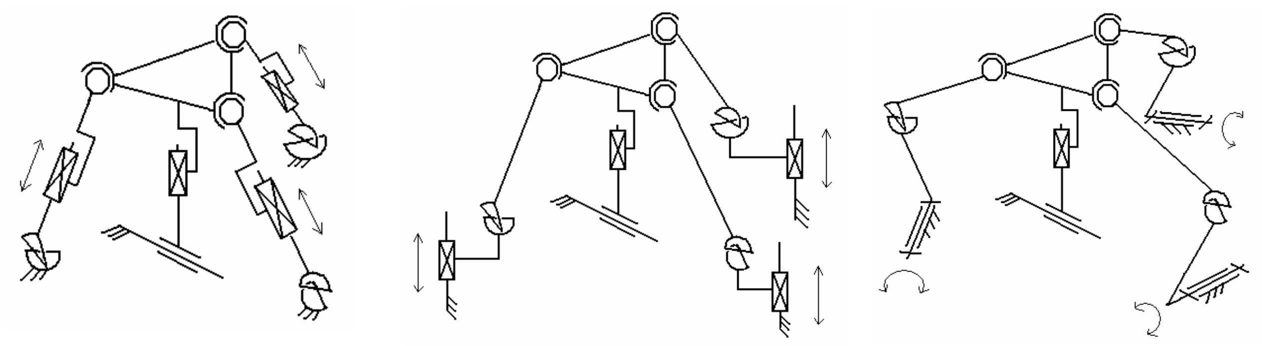
This work introduces a new family of 3-dof parallel robot manipulators for pick-and-place operations. Its feasible topologies are enumerated by describing its possible forms of actuation. Important issues such as the position kinematics and workspace evaluation are analysed for one member of the family. Finally, a built prototype is shown to verify the accordance of its kinematic behaviour with the one predicted by the mathematical model.

2. Topology generation

There are many different approaches for topology generation of parallel kinematic structures. Hervé (1978) introduced the algebraic group structure of the displacement set, which is based on the mathematics of the motion group. The method of enumeration of active limbs was first proposed by Hunt (1983) and expanded later by Tsai (1999). Other alternative methods are either based on the screw theory (Kong and Gosselin, 2004) or even on the addition of a passive limb (Brogard, 2002).

The method of addition of a passive limb, which we applied in this paper, considers that the moving platform motion is constrained by a passive limb connected to it. In fact, the passive limb is carefully chosen in such a way that the number of degrees of freedom, F, and type of available motions for the end-effector correspond to the desired ones. Besides, partial connectivities of remaining m active limbs must be equal to λ, the space dimension where the mechanism is supposed to function.

In our case, we selected a passive limb composed by two joints: a cylindrical (C) and a prismatic (P) one. As a consequence, the moving platform has three degrees of freedom and is constrained to perform two translations and one rotation. The connectivities of the other three active limbs must be equal to six. If we assume that each active limb has only two links and three joints, then the sum of degrees of freedom of the three joints is equal to six. By employing different joints in each limb, we can use prismatic (P), revolute (R), universal (U) and spherical (S) joints. Then, a family of parallel mechanisms (fig.1) is formed by the following architectures: *3 UPS + CP, 3 PUS + CP* and *3 RUS + CP*. An underlined letter is an active joint, which states the presence of an actuator. One can observe that all actuators are at or near the base. Constructively, all actuators can be rotary electrical motors even for members (a) and (b), because their output shafts might be coupled to ball-screws devices. The following sections will deal with the position kinematics and workspace evaluation are analysed for one member of the family: the *3 RUS + CP*.



a b c

Fig. 1 – Skeleton kinematic diagram of the members of the family: (a) *3 UPS+CP*; (b) *3 PUS+CP*; (c) *3 RUS+CP*.

3. Position kinematics

The objective of position kinematics is to determine the mathematical transformation between the coordinates *x*, *y* and *z*, of a point P that belongs to the platform, and actuator displacements θ_1, θ_2, and θ_3. After obtaining such relations, it is possible to perform inverse and direct kinematics, singularity analysis and workspace evaluation. Due to the fact that our control strategy is performed in joint space, only inverse kinematics will be necessary.

$$T:\ x, y, z \ \rightarrow\ \theta_1, \theta_2, \theta_3$$

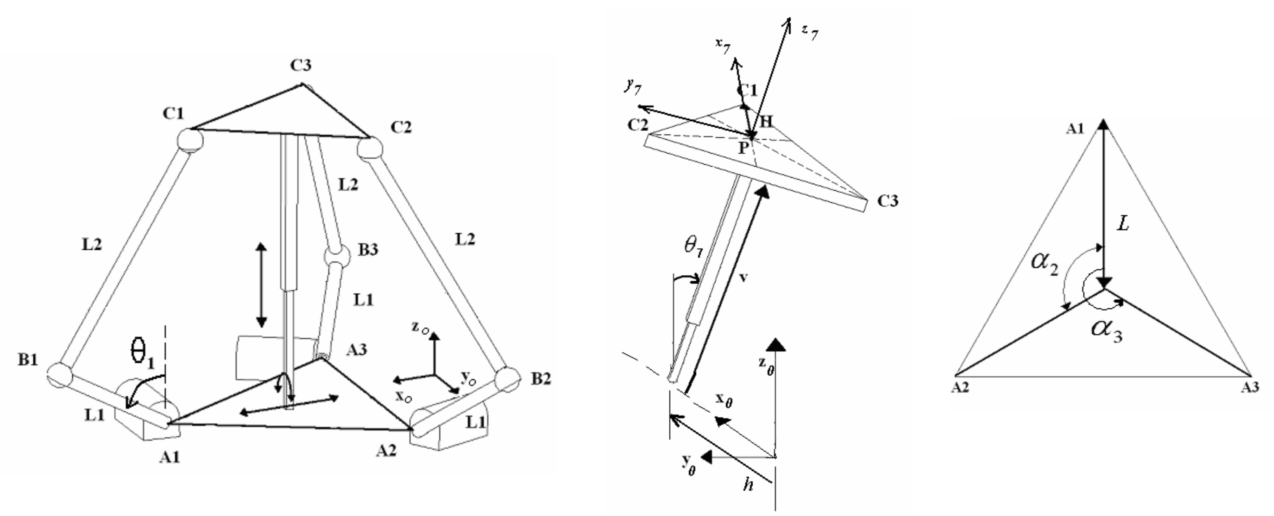


Fig.2 - Simbology for position analysis.

This analysis starts by calculating the relation between the point *P* coordinates and the auxiliar variables *h*,*v* and θ_7, that correspond to the displacement along *x*-axis, z_7-axis and rotation around *x*-axis, respectively. We describe the location of this point by the homogeneous transformation (Craig, 1989) of frame *7* with respect to the fixed frame *0*, ${}^0_7T$.

$$\begin{bmatrix} {}^0P \\ 1 \end{bmatrix} = {}^0_7T \cdot \begin{bmatrix} {}^7P \\ 1 \end{bmatrix} \qquad (1)$$

Then,

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & h \\ 0 & c\theta_7 & -s\theta_7 & -v \cdot s\theta_7 \\ 0 & s\theta_7 & c\theta_7 & v \cdot c\theta_7 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} h \\ -v \cdot s\theta_7 \\ v \cdot c\theta_7 \\ 1 \end{bmatrix} \tag{2}$$

After describing the location of point P, we can also determine the center of each spherical joints C_j

$$\begin{bmatrix} {}^{0}C_j \\ 1 \end{bmatrix} = {}^{0}_{7}T \cdot \begin{bmatrix} {}^{7}C_j \\ 1 \end{bmatrix} \tag{3}$$

Then,

$$\begin{bmatrix} {}^{0}C_j \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & h \\ 0 & c\theta_7 & -s\theta_7 & -v \cdot s\theta_7 \\ 0 & s\theta_7 & c\theta_7 & v \cdot c\theta_7 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} H \cdot c\alpha_j \\ H \cdot s\alpha_j \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} H \cdot c\alpha_j + h \\ (H \cdot s\alpha_j) \cdot c\theta_7 - v \cdot s\theta_7 \\ (H \cdot s\alpha_j) \cdot s\theta_7 + v \cdot c\theta_7 \\ 1 \end{bmatrix} \quad j = 1,2,3 \tag{4}$$

The point B_j is the center of the universal joint in each limb j (fig.3)

$$\begin{bmatrix} {}^{0}B_j \\ 1 \end{bmatrix} = {}^{0}_{j}T \cdot {}^{j}_{j+3}T \cdot \begin{bmatrix} {}^{j+3}B_j \\ 1 \end{bmatrix} \quad j = 1,2,3 \tag{5}$$

where

$${}^{0}_{j}T = \begin{bmatrix} c\alpha_j & -s\alpha_j & 0 & Lc\alpha_j \\ s\alpha_j & c\alpha_j & 0 & Ls\alpha_j \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{j}_{j+3}T = \begin{bmatrix} c\theta_j & 0 & s\theta_j & 0 \\ 0 & 1 & 0 & 0 \\ -s\theta_j & 0 & c\theta_j & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{j+3}B_j = \begin{bmatrix} 0 \\ 0 \\ L_1 \end{bmatrix}$$

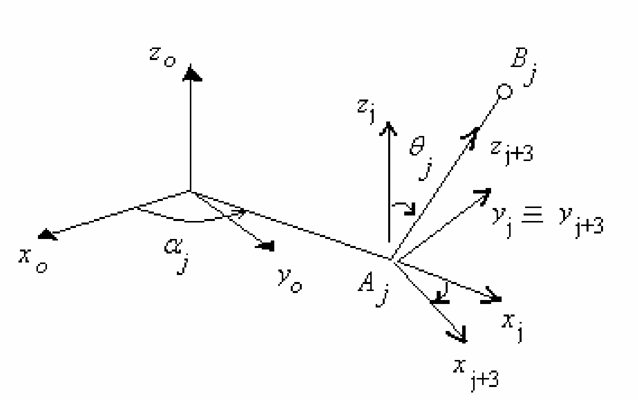


Fig.3 - Sketch of limb j indicating used reference frames.

Therefore,

$${}^{0}B_j = \begin{bmatrix} (L_1 \cdot c\alpha_j) \cdot s\theta_j + Lc\alpha_j \\ (L_1 \cdot s\alpha_j) \cdot s\theta_j + Ls\alpha_j \\ L_1 c\theta_j \end{bmatrix} \tag{6}$$

The distance between points B_j and C_j is equals to L_2.

$$\left({}^{0}B_j - {}^{0}C_j\right)^T \left({}^{0}B_j - {}^{0}C_j\right) = L_2^2 \quad j = 1,2,3 \tag{7}$$

Then,

$$K_j \cdot c\theta_j + M_j \cdot s\theta_j + N_j = 0 \qquad j = 1,2,3 \tag{8}$$

where

$$K_j = 2L_1 \cdot \left(-Hs\alpha_j s\theta_7 - vc\theta_7\right)$$

$$M_j = 2L_1 \cdot \left(c\alpha_j \cdot \left((L-H)\cdot c\alpha_j - h\right) + s\alpha_j \cdot \left((L - Hc\theta_7)\cdot s\alpha_j - v \cdot s\theta_7\right)\right)$$

$$N_j = L_1^2 + \left((L-H)\cdot c\alpha_j - h\right)^2 + \left((L - Hc\theta_7)\cdot s\alpha_j - v \cdot s\theta_7\right)^2 + \left(-Hs\alpha_j s\theta_7 - vc\theta_7\right)^2$$

Eq. (8) can be modified into a 2th-order polynomial equation

$$\left(N_j - K_j\right)\cdot u_j^2 + \left(2M_j\right)\cdot u_j + K_j + N_j = 0 \qquad j = 1,2,3 \tag{9}$$

where

$$u_j = tan\left(\frac{\theta_j}{2}\right)$$

As one can notice, eq. (9) may have up to two different solutions and, as a consequence the mechanism itself may have up to eight assembly modes. These assembly modes are only theoretically possible and, consequently, due to constructive reasons, one among the others is preferrable. The chosen assembly mode represented in fig.2 is adequate because it avoids interference between each peripheral active limb with the central passive one.

4. Workspace evaluation

The available workspace of the *3 <u>R</u>US+CP* represents a 3D-region where point P, that belongs to the moving platform, can move. To determine this workspace, the discretization method (Hess-Coelho and Raszl, 2004) is employed. This method considers that the workspace is determined from a solid, assumed larger than the feasible workspace, discretized by a regular mesh. Then, a procedure checks whether or not each mesh node violates the physical and kinematic constraints. Consequently, workspace boundaries are composed by a set of nodes that have at least one node neighbor that does not belong to the workspace.

The physical constraints are represented by the displacement range of cylindrical, prismatic, spherical and universal joints. In addition, another important factor refers to the kinematic constraints. Our analysis verifies any inconsistency that may arise when solving position kinematic equations. In such cases, there is a strong evidence that the mechanism reached a singular configuration.

Table 1 – Parameters of parallel mechanism

H [mm]	L [mm]	L_1 [mm]	L_2 [mm]	α_1 [^{0}]	α_2 [^{0}]	α_3 [^{0}]
85	119	90	210	0	120	240

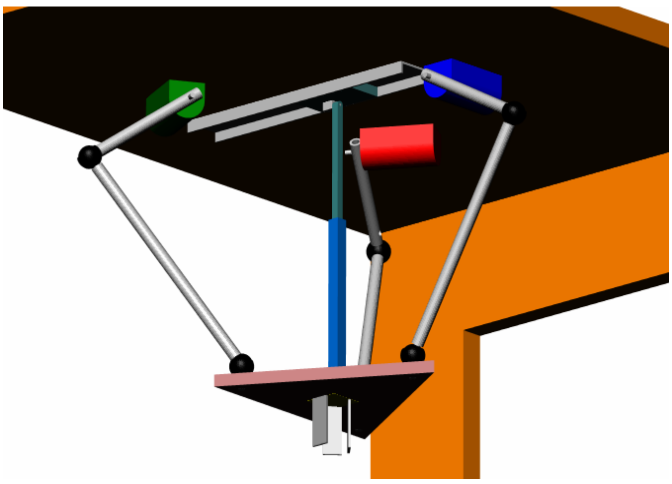
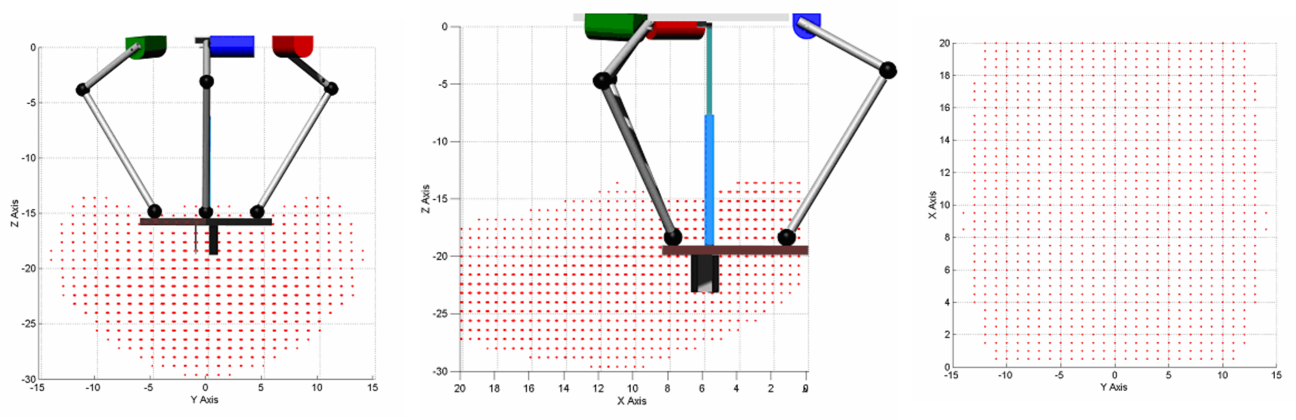


Fig. 4 – CAD model of *3 <u>R</u>US+CP*.



a b c

Fig.5 – Available workspace in three different views: (a) y-z plane; (b) x-z plane; (c) x-y plane.

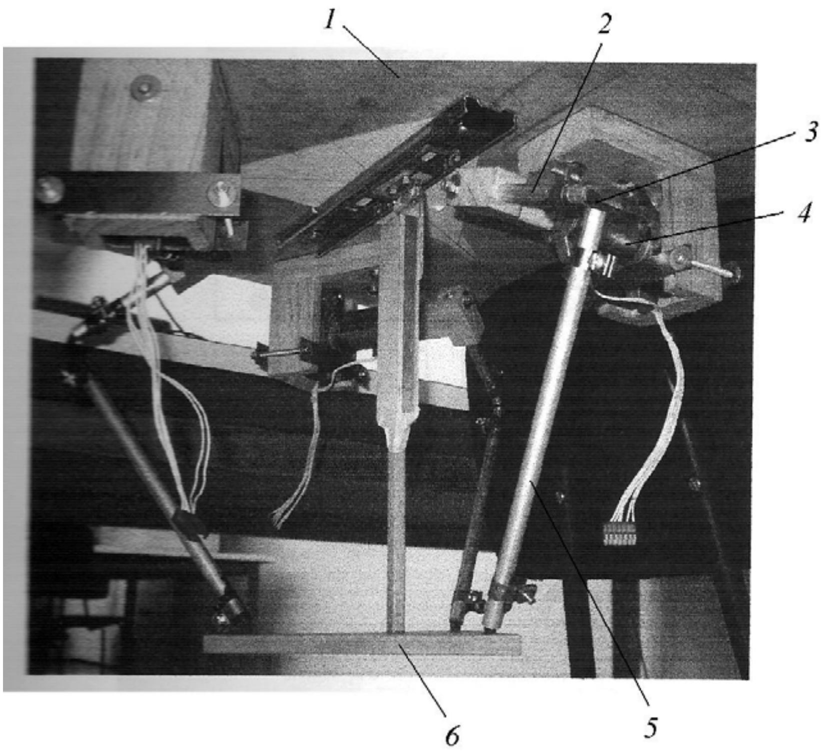


Fig. 6 – Built prototype: (1) base, (2) shorter link, (3) joint, (4) actuator, (5) longer link, (6) moving platform.

The volume of the available workspace is aproximately 7.2 dm^3. The ratio between the workspace and the area occupied by the mechanism is 1.2 *dm* . In a comparison with other parallel robots, by using this performance index as a valid criterium, Tripteron (Gosselin et al., 2004) and Delta robot (ABB, 2005) reach 0.9 *dm* and 2.5 *dm*, respectively. Thus, our proposed parallel mechanism, despite the fact that its parameters were not optimized, presents a performance comparable to these robots.

5. The built prototype

The built prototype, shown in fig.6, is formed by the following subsystems: mechanical, actuator and control. The mechanical subsystem is essentially the parallel mechanism described in previous sections, which contains a fixed base and a moving platform, both connected by one passive and three active kinematic chains. In each active kinematic chain, the universal and spherical joinst are constructivelly replaced by flexible rubber couplings, while in the passive kinematic chain, the cylindrical joint is substituted by prismatic and revolute joints. Three electrical DC servomotors and their respective drivers (IC 3524) compose actuator subsystem. Control subsystem includes a PC computer, three servomotor controllers (Motorola M68EVB908Q), three angular encoders, a communication cable, and an inverse kinematics model, written in MatLab that calculates actuator displacements from a specified sequence of end-effector positions. Servomotors are controlled by using pulse width modulation (PWM) and their maximum positioning resolution is 0.71 degree/pulse. This prototype was tested under the same conditions analysed by the mathematical model. When the moving platform performed its basic motions, the predicted workspace was aproximately reached by the prototype.

6. Conclusions

A new family of 3-dof parallel robot manipulator was presented. The paper described the topology generation process and showed three alternative structures depending on the forms of actuation. The inverse position kinematics of one member of the family, the *3 RUS + CP*, was developed. Available workspace was evaluated and compared with other parallel robots. By observing the kinematic behaviour of the built prototype, we foresee a promissing future for this parallel mechanism as a pick-and-place robot.

7. Acknowledgements

To Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for sponsoring this research (process No. 03/13862-9).

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