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# TRI-SCOTT. A MICABO like 6-DOF Quasi-Decoupled Parallel Manipulator

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**Abstract:** *This paper describes a variant of the six-DOF MICABO parallel manipulator. It is analyzed the planar decoupled movement of the moving platform arising from the usage of three SCOTT mechanism. This makes possible the use of Gosselin et al three degree planar mechanisms polynomial solution for the direct kinematic position analysis. The degrees of freedom the inverse kinematics and the different assembly modes of the mechanism are also presented.*

## 1 Introduction

The kinematic structure of most contemporary robots is an open kinematic chain structure (serial manipulators). However, robots with closed kinematic chains (parallel manipulators) have some advantages compared to serial ones:

- Higher payload to weight ratio, since the payload is supported by several legs in parallel.
- Higher accuracy due to non-cumulative joint error.
- Higher structural rigidity due to closed kinematic structure.
- Stationary position configurations with very high position precision for the output link.
- Usually, actuators are located on the fixed platform.
- Simple solution of the inverse kinematics equations.
- Conversely, they suffer from smaller work space, uncertainty position configurations and more complicated direct kinematic solution.

One of the first parallel manipulators, patented by Pollard (1942), was used for car painting. Later, Gough and Whitehall (1962) presented a parallel manipulator for tire testing and Stewart (1965) another one used in a fly simulator, both manipulators having linear actuators. Hunt (1983) presented a new parallel manipulator structure with 6 rotary actuators. During these last decades many authors have proposed different parallel kinematic structures, some of them with linear actuators, others with rotary actuators and some with a mixture of linear and rotary actuators. Several of these parallel manipulators are shown in (Merlet 2000). Also, these and other examples and references can be found at the following URLs:

- [http://www-sop.inria.fr/coprin/equipe/merlet/merlet.html].
- [http://www.parallemic.org/].

In most parallel manipulators, a particular actuator movement influences both position and moving platform orientation, but in some it influences only the position or only orientation. These are called **decoupled manipulators**.

This term must be carefully interpreted because most parallel manipulators present some degree of coupling. As an example imagine a manipulator with six linear actuators in which three of them are attached to a single point at the moving platform. If these actuators are fixed the movement of the remaining actuators will influence only the platform orientation. However if any of the above fixed actuators moves both position and orientation will change simultaneously. Nevertheless these parallel manipulators are frequently called decoupled in the literature.

Examples of different decoupled parallel manipulator structures are presented for Innocenti and Parenti-Castelli (1991), Zlatanov et al. (1992), Patarinski and Uchiyama (1993), Wohlhart (1994), Geng and Haynes (1994), Bernier et al. (1995), Lee (1995), Lallemand et al. (1997), Ben-Horin et al. (1998), Brodski et al. (1998), Mianowski (1998) and Lee and Park (1999).

Among these manipulators only the Mianowski one can be considered fully decoupled regarding to the strict definition stated above.

## 2 TRI-SCOTT structure

The parallel manipulator (Fig. 1) is composed of one fixed platform with three masts, three modified Scott's mechanisms sliding on the masts, and a triangular moving platform.

The masts are fixed and perpendicular to the fixed platform and located at the vertexes of a triangle. At each Scott's mechanism two of the turning pairs have been replaced by two universal joints (U) allowing them to have a spatial movement instead of a planar one. Each complete Scott's mechanism can slide on its corresponding mast. The three vertexes of the moving platform are attached to the three ending points of the Scott's mechanisms (points 41, 42 and 43).

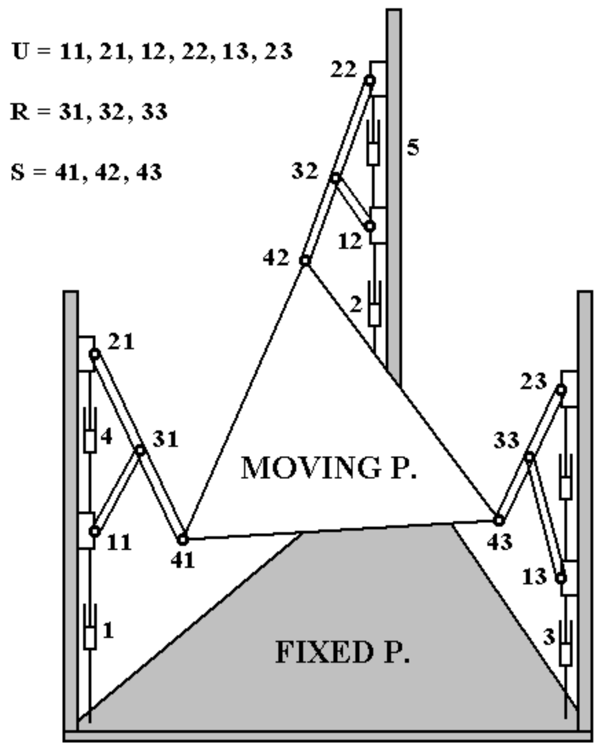


Figure 1. Tri-Scott parallel manipulator

At each mast, the overall movement of the complete Scott's mechanism is introduced by one linear actuator (actuators 1, 2 and 3), attaching the mechanism to the fixed platform. The intrinsic movement in each Scott's mechanism is introduced by one linear actuator (actuators 4, 5 and 6), attaching both mechanism sliders, being this the main difference in relation to the MICABO mechanism.

The similar MICABO parallel manipulator, was patented by Hesselbach et al (1998) and developed by Hesselbach and Kusiek (2000), in this case 4, 5 and 6 actuators replaced by similar ones acting between the fixed platform and the upper part of the depicted Scott's mechanisms.

Thus the properties of the Scott's mechanisms regarding the decoupling are not fully exploited.

The Scott's mechanism is also exploited in a parallel manipulator patented by Kazuya in Japan. In this case all the actuators are placed in a single plane being one couple perpendicular to the other two. Thus the mechanism is not decoupled.

## 3 TRI-SCOTT kinematics

The original Scott's mechanism (Fig. 2) is a planar straight-line mechanism. With appropriate dimensions point "P" describes a straight line. In this mechanism, the pairs "A", "B" and "C" are revolutes.

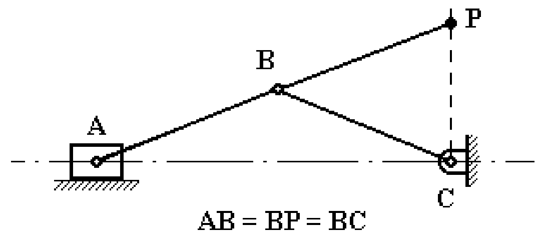


Figure 2. Original Scott's mechanism

Replacing the original Scott's mechanism turning pairs "A" and "C" by two spherical pairs (S) or by two universal joints (U) with two of their turning pairs aligned, a spatial mechanism is obtained in which point "P" moves on a plane. Placing pair "C" on a slider, the complete mechanism can have an overall sliding motion on the mast, (Fig. 3).

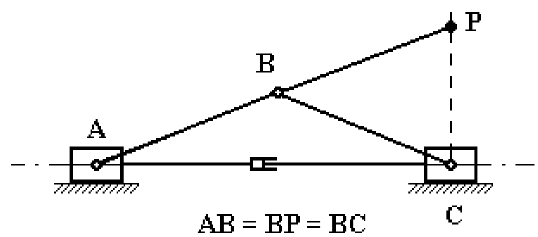


Figure 3. Modified Scott's mechanism

Due to the characteristics of such modified Scott's mechanisms, a quasi-decoupled movement of the moving platform is obtained. For example, if movement is only introduced by actuators "4", "5" and "6", a **planar movement** of the moving platform is obtained.

The above statement is also true in the MICABO structure, the only difference being a slightly greater decoupling in the case of Tri-Scott, because a rectilinear only movement can be attained if the lower actuators move at the same velocity. This is because Scott's mechanisms internal movement vanishes if only 1, 2 and 3 actuators are moving. Obtaining the same behavior in MICABO implies the movement of the six actuators at the same rate.

So, although this manipulator does not fulfills the decoupled manipulator definition stated at the beginning, it can be claimed that it exhibits a great degree of decoupling in the sense that it allows a planar movement with the use of any of the three lower actuators and a rectilinear movement -perpendicular to the planar movement- using the remaining three. Conditions that can be advantageous in the design of machine tooling operations.

So, not fulfilling completely the decoupled manipulator definition, we define it as a quasi-decoupled mechanism.

It is clear that the mechanisms exhibits 6 degrees of freedom. Using the Kutzbach criterion, having into account that pairs 11, 21, 12, 22, 13 and 23 can be spherical or universal joints with two of their turning pairs aligned, the moving platform degrees of freedom are easily found:

$$DOF = 6 \cdot (14 - 1) - 5 \cdot 9 - 3 \cdot 9 = 6 \quad (1)$$

### 3.1 TRI-SCOTT notation and topology

The notation used to describe the topology of this parallel manipulator is summarized in the following items and shown in figures 1, 4 and 5.

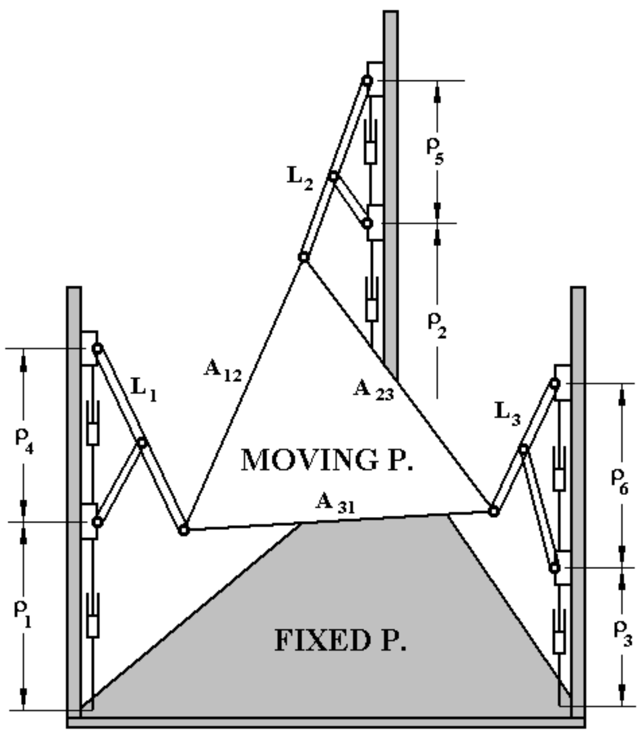


Figure 4. Notation in the parallel manipulator. Perspective.

Actuators numeration and coordinates:
- *i* Linear actuator.
- $\rho_i$ Articular coordinate of the *i-th* actuator.

Characteristc points:
- *1i* Center of universal joint in the lower slider of the *i-th* Scott's mechanism.
- *2i* Center of universal joint in the upper slider of the *i-th* Scott's mechanism.
- *3i* Center of turning pair in the *i-th* Scott's mechanism.
- *4i* Center of the spherical joint, vertex of moving platform attached to *i-th* Scott's mechanism.

Characteristic dimensions:
- *Li* Length between centers *2i* and *4i*, or length of the longer link of the *i-th* Scott's mechanism.
- *Aij* Length moving platform edge that links the *i-th* and *j-th* Scott's mechanisms.
- *L'i* Length of the horizontal projection of *Li*, or length between centers *1i* and *4i*.
- *A'ij* Length of the horizontal projection of the edge *Aij*.

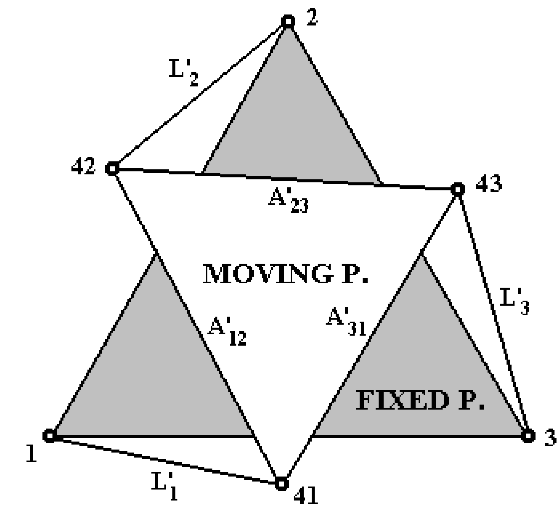


Figure 5. Notation in the parallel manipulator. Horizontal projection.

## 4 Inverse kinematics

Inverse kinematics deals with the determination of the articular coordinates in terms of the moving platform position.

The moving platform position is expressed in terms of the value of the coordinates of the moving platform vertexes ( $X_{4i}, Y_{4i}, Z_{4i}$ ).

It must be noted that although the position of the moving platform can be stated in a different way, for example by means of the coordinates of its gravity center and three Euler angles, it is always easy to determine the coordinates of its three above mentioned vertexes in terms of the alternative set of coordinates.

It is evident that in the Scott's mechanism the articular coordinates of "1", "2" and "3" actuators are de "Z" coordinates of the moving platform vertexes, so

$$\rho_i = Z_{4i} \quad ; \quad i = 1,2,3 . \quad (2)$$

And, as

$$L'_i = \sqrt{L_i^2 - \rho_{i+3}^2} , \quad (3)$$

the articular coordinates of "4", "5" and "6" actuators will be:

$$\rho_4 = \sqrt{L_1^2 - (X_{41} - X_1)^2 - (Y_{41} - Y_1)^2} \tag{4}$$

$$\rho_5 = \sqrt{L_2^2 - (X_{42} - X_2)^2 - (Y_{42} - Y_2)^2} \tag{5}$$

$$\rho_6 = \sqrt{L_3^2 - (X_{43} - X_3)^2 - (Y_{43} - Y_3)^2} \tag{6}$$

## 5 Direct kinematic

Direct kinematic deals with the determination of moving platform position in terms of the input (actuator) coordinates.

Given the articular coordinates "$\rho_i$", the "$Z_{4i}$" coordinates of the of moving platform vertexes are directly determined:

$$Z_{4i} = \rho_i \quad ; \quad i = 1,2,3. \tag{7}$$

The lengths of the horizontal projections of the longer links in the Scott's mechanisms will be:

$$L_1^{'} = \sqrt{L_1^2 - \rho_4^2} \tag{8}$$

$$L_2^{'} = \sqrt{L_2^2 - \rho_5^2} \tag{9}$$

$$L_3^{'} = \sqrt{L_3^2 - \rho_6^2} \tag{10}$$

And the lengths of the horizontal projections of the edges of moving platform will be:

$$A_{12}^{'} = \sqrt{A_{12}^2 - (Z_{42} - Z_{41})^2} \tag{11}$$

$$A_{23}^{'} = \sqrt{A_{23}^2 - (Z_{43} - Z_{42})^2} \tag{12}$$

$$A_{31}^{'} = \sqrt{A_{31}^2 - (Z_{41} - Z_{43})^2} \tag{13}$$

Taking into account the lengths of the projections, equations (8 to 13), the coordinates "X" and "Y" of the vertexes of the moving platform can be determined with the polynomial method proposed by Gosselin et al. (1992) for planar parallel manipulators.

Gosselin et al. obtained a sixth degree polynomial which could get six real solutions, corresponding to the different assembly modes of the manipulator.

As Tri-Scott is a spatial mechanism, its moving platform can turn upside down, for this reason, the Tri-scott have another six degree polynomial with another six possible solutions.

As a consequence, the direct kinematics of the Tri-Scott parallel manipulator presents two sixth degree polynomials with twelve possible solutions associated with different assembly modes of the manipulator.

## 6 Conclusions

In this paper the quasi-decoupled nature of a MICABO like six DOF parallel manipulator has been analyzed as a consequence of the usage of three modified Scott's mechanisms. With this structure quasi-decoupled planar and linear movements implying respectively the use of two different sets of actuators are obtained. The inverse kinematics of the manipulator is presented. Finally, it is demonstrated how it is possible to obtain a closed form direct kinematics, using the Gosselin et al polynomial method in planar three DOF mechanisms, in terms of two polynomials of sixth degree that have associated twelve different assembly modes.

## References


Ben-Horin R., Shoham M, and Djerassi S., 1998, "Kinematics, dynamics and construction of a planarly actuated parallel robot", Robotics and Computer-Integrated Manufacturing, Vol. 14, Nº 2, pp. 163-172.

Bernier D., Castelain J.M., and Li X., 1995, "A new parallel structure with six degree of freedom", 9th World Congress on the Theory of Machines and Mechanisms", Milan, August 30-September 2, pp. 8-12.

Brodski V., Glozman D., and Shoham M., 1998, "Double circular-triangular six-degree-of-freedom parallel robot", ARK, Strobl, June 29-July 4, pp. 155-164.

Geng Z., and Haynes L.S., 1994, "A 3-2-1 kinematic configuration of a Stewart platform and its application to six degree of freedom pose measurements", Robotics & Computer-Integrated Manufacturing, Vol. 11, Nº 1, pp. 23-34.

Gosselin C.M., Sefrioui J., and Richard M.J., 1992, " Solutions polynomiales au problème de la cinématique directe des manipulateurs parallèles plans à trois degrés de liberté", Mechanism and Machine Theory, Vol. 27 Nº 2, pp. 107-119.

Gough V.E., and Whitehall S.G., 1962, "Universal tire test machine", Proc. 9th Int. Technical Congress F.I.S.I.T.A., Vol. 117, pp. 117-135.

Hesselbach J., Kerle H., Thoben R., and Plitea N. 1998, "Manipulator for parallel structure and driven guide elements", German patent Nº DE19710171.

Hesselbach J., and Kusiek A., 2000, "Machinennahe steuerungsfunktionen für parallelroboter", Working Accuracy of Parallel Kinematics, Chemnitz, 12-13 April.

Hunt K.H., 1983, "Structural kinematics of in-parallel-actuated robot-arms", J. of Mechanisms, Transmissions, and Automation in Design, Vol. 105, Nº 4, pp. 705-712.

Innocenti C., and Parenti-Castelli V., 1991, "Direct kinematics of the 6-4 fully parallel manipulator with position and orientation uncoupled" European Robotics and Intelligent Systems Conf., Corfu, June 23-28.

Kazuya H., "Mono-axis type 6 degree-of freedom", Japanese patent, [http://www.hephaist.co.jp/egdex99.html].

Lallemand J.P., Goudali A., and Zeghloul S., 1997, "The 6-dof 2-Delta parallel robot", Robotica, Vol. 15, Nº 4, pp. 407-416.

Lee M.K., 1995, "Design of a high stiffness machining robot arm using double parallel mechanism", IEEE Int. Conf. on Robotics and Automation, Nagoya, May 25-27, pp. 234-240.

Lee M.K., and Park K.W., 1999, "Kinematics and dynamics analysis of a double parallel manipulator for enlarging workspace and avoiding singularities", IEEE Trans. on Robotics and Automation, Vol. 15, Nº 6, pp. 1024-1034.

Merlet J.P., 2000, "Parallel robots", Kluwer Academic Publishers.

Mianowski K., 1998, Dextrous fully parallel manipulator with six degrees of freedom", 12th RoManSy, Paris, July 6-9, pp. 253-260.

Patarinski S.P., and Uchiyama M., 1993, "Position/ orientation decoupled parallel manipulator", ICAR, Tokio, November 1-2, pp. 153-158.

Pollard W.L.V., 1942, "Position controlling apparatus", United States Patent Nº US2286571.

Stewart D., 1965, "A platform with 6 degree of freedom", Proc. of the Institution of Mechanical Engineers, Vol. 180, Pt. 1, Nº 15, pp. 371-386.

Wohlhart K., 1994, "Displacement analysis of the general spherical Stewart platform", Mechanisms and Machine Theory, Vol. 29, Nº 4, pp. 581-589.

Zlatanov D., Dai M.Q., Fenton R.G., and Benhabib B., 1992, "Mechanical design and kinematic analysis of a three-legged six degree-of-freedom parallel manipulator", Robotics, Spatial Mechanisms, and Mechanical Systems, ASME, DE-Vol 45, pp. 529-536.