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Motion pattern analysis of parallel kinematic machines: A case study

Oscar Altuzarra [a,*], Yon San Martín [b], Enrique Amezua [a], Alfonso Hernández [a]

[a] Department of Mechanical Engineering, University of the Basque Country, UPV/EHU, Alameda de Urquijo, s/n, Bilbao 48013, Vizcaya, Spain
[b] Fatronik Foundation,Polígono Ibaitarte, 1-Apdo. Correos 160-Elgoibar 20870 (Spain)

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ABSTRACT

This paper looks at the "five-axis machines" for machining operations. These machines have five (or six at maximum) degrees of freedom (dof). The output motion must have at least three translational and two rotational dof. This output motion pattern can be obtained with different structural topologies: serial, parallel, hybrid and with serial and/or parallel manipulators working in co-operation. The latter allows higher motion ranges in rotational and translational dof. Moreover, it provides a good stiffness, a highly valued requisite in applications like machining. Manipulators of this type are characterized by their kinematics to be integrated in the CNC, which requires the study of the relative motion between their modules. This motion is usually complex, and in certain cases presents kinematic relations not evident. This work presents a methodology to solve the motion pattern out of the direct and inverse kinematics of the relative motion between the modules of which the manipulator is composed. On the one hand, the spindle is mounted on a parallel module. On the other hand, the working table is mounted on a serial module. This methodology was applied to the Hermes parallel manipulator in combination with rotary and linear tables. As a result, a series of considerations regarding other possible combinations between modules was made and a new machine is proposed.

1. Introduction

Five-axis machines of serial structure are widely used for certain machining operations in many industrial sectors. Rotational axes are usually located in a bi-rotary head. Sometimes, one of the translational axes is removed from the head module and taken to the working table. This latter procedure is mainly used for the machining of large dies and molds, as well as for large aeronautical parts. An inverse structure is also possible locating the three translational dof (3 T) within the head and a rotary table to provide rotational axes.

The main problems of five-axis serial machines come from their limitations in terms of static stiffness and vibrations. These are mainly due to the flexibility of mechanical transmissions that use gears to provide the rotation between elements.

In the beginning, the five degrees of freedom (dof) parallel manipulators that appeared as an alternative to serial machines, typically had a Gough–Stewart platform kinematic structure. Examples of these manipulators are: the Giddings & Lewis Variax [1], the Octahedral Hexapod HOH-600 [2] and the Octahedral Hexapod VOH-1000 [3] both by Ingersoll, the Mikromat 6X [4] or the Okuma Cosmo Center PM-600 [5]. The Toyoda HexaM structure [6] is similar, although it is really a 6-PUS parallel manipulator. However, they have considerable limitations in rotational capacity (non-existent in the above) making it impossible to achieve five-face machining. Their dimension is another important limitation. These parallel manipulators are very large in relation to the workspace they can reach.

So as to improve angle range, some parallel manipulators have been designed with a structure differing from the Gough–Stewart platform. This is the case in the Daeyoung Machinery Eclipse-RP [7] or in the METROM P800 [8]. However, these machines still suffer from an excessive size to workspace ratio.

One way of reducing this ratio is to combine serial elements with parallel ones giving rise to the so-called hybrid robots, as in the Neos Robotics Tricept [9]. A serial wrist mounted on the parallel structure improves the ratio, as well as increases the tilting angles in relation to previous designs. However, it does not solve problems of stiffness very well, since it uses a head very similar to that of the serial machines.

Another hybrid machine is the Fatronik's Space5 H [10] (Fig. 1). This machine consists of a HERMES parallel manipulator mounted on a two-dof translational (2T) module. This machine is designed for the manufacturing of large parts in the aeronautical sector. Its performance features are very good although five-face machining is not possible. A similar solution is found in the ECOSPEED machine [11] that uses a DS Technology SPRINT Z3 head.

* Corresponding author. Tel.: +34 94 6014174; fax: +34 94 6014215.
E-mail address: oscar.altuzarra@ehu.es (O. Altuzarra).

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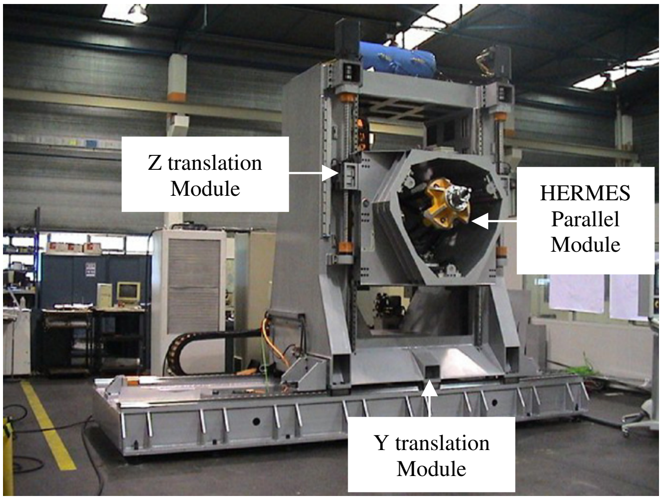

Fig. 1. Machine-tool Hermes in series with two linear translations.

There is yet another alternative with possibilities for increasing tilting angles, that still allows five-face machining and reduces machine size. This alternative is to split the machine in two separate modules, which work in co-operation, of three and two dof, respectively. For example, a simple structure suitable for machining small and complex parts is one comprising a head with three translations in series, and a tilting rotary table with two rotational dof (2R), also in series.

A variant of this structure is the Chiron's VISION [12]. The first module is a hybrid comprising a vertical axis locating the tool, mounted on a two-dof translational parallel structure. The second module is a tilting rotary table. The relative motion of three-dof tool (3T) in relation to the rotary table (2R) effectively creates a five-axis machine enabling five-face machining. Another variation, this time for medical applications [13], combines a three-dof (1T2R) parallel module (3-RPS) with a linear table (2T).

Likewise, the combination of a four-dof module with a one-dof table is possible. However, the performance features of the previous cases are rarely attained. For example, the HITA-STT manipulator [14] combines a four-dof parallel module (3T1R) with a rotary table (1R). Another alternative is the combination of a hybrid module (2T2R) with a linear table [15].

There are probably more combinations for obtaining five-axis machines. Below, however, is a summary of the ones mentioned before:

- SERIAL (3T2R)
- PARALLEL-Gough (3T3R)
- PARALLEL-Other architectures (3T2R)
- HYBRIDS:
  - PARALLEL-SERIAL (3T2R)
  - SERIAL-PARALLEL (3T2R)
- TWO MODULES:
  - SERIAL (3T)+Rotary Table (2R)
  - HYBRID (3T)+Rotary Table (2R)
  - PARALLEL (1T2R)+Linear Table (2T)
  - PARALLEL (3T1R)+Rotary Table (1R)
  - HYBRID (2T2R)+Linear Table (1T)

Of these options, this paper will focus on those involving two modules. As already stated, the tool is set in one module and the part to be machined in another. This generates an interest in the kinematics of the relative motion between both modules.

One can observe in all the cases above, that the union between the dof's of one module and the other always gives the desired set of dof's, i.e., 3T and 2R. Furthermore, in all cases, one of the modules has exclusively translational dof's. Under these circumstances, the kinematics of relative motion is simple, since it is sufficient to subtract this translation from the motion of the other module.

In this paper, a case whose kinematics has not been analyzed in the bibliography is studied. What will happen when one module is a three-dof manipulator of the type 1T2R and the other a two-dof tilting rotary table? Is it possible to achieve five independent dof's for relative motion of the type 3T2R? How can the resulting motion pattern be obtained? As none of the module generates only translations, how can the kinematics of the relative motion between the two modules be solved? These questions will be answered methodically in the following sections.

The reason for using modules with so many rotational dof's is not mere caprice, but pragmatic where there is a necessity to increase tool rotations in relation to the part and to reduce the footprint of the machine.

2. Position problems in relative motion

This section presents the scheme to solve the relative position problems between the mechanism holding the tool and the one holding the part. As the problem is approached from an industrial point of view, the position problem solved is the finite displacement problem using a Newton–Raphson scheme and looking for one solution. We take as a starting point the solution of these problems in absolute motion.

The coordinate systems used are (Fig. 2):

- A fixed reference system F (O_F, X, Y, Z), which corresponds to the machine reference frame.
- A reference system T (O_T, U_T, V_T, W_T) on the platform where the tool is to be installed.
- A reference system P (O_P, U_P, V_P, W_P) on the working table where the part is to be placed.

2.1. Position equations in relative motion

The motion of the tool relative to the part system is defined by the corresponding transformation matrix:

$$ {}^{P}_{T}\mathbf{T} = \begin{bmatrix} {}^{P}_{T}\mathbf{R} & {}^{P}_{T}\mathbf{d} \\ 0 & 1 \end{bmatrix} \tag{1} $$

where ${}^{P}_{T}\mathbf{R}$ is the rotation matrix and ${}^{P}_{T}\mathbf{d}$ denotes the tool position relative to the part coordinate system.

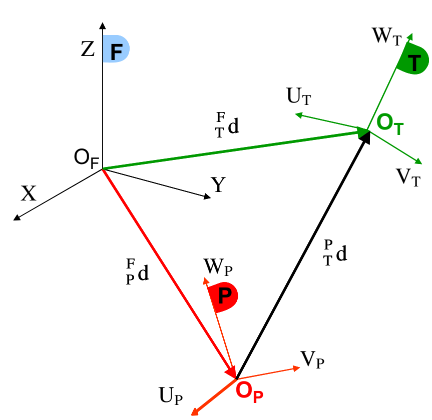

Fig. 2. Reference coordinate systems.