Kinematic Modeling of a Parallel Machine Tool in High Speed Machining UGV

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Abstract

The aim of this study is to obtain position and orientation of a trajectory frame with respect to the fixed frame of the manipulator. The work path which is given the modeling of a Three Slider Manipulator (TSM) of 3-PUU type (U: universal joint, P: prismatic joint). His type of mechanism consists of three linear motors, where the moving platform is connected with the actuators by three links. In this paper we representing the interest of modeling made a modeling of a parallel machine tool with three axes, used in machining at high speed. This modeling is the base of all the studies relating to this type of the mechanisms.
Keywords: *Kinematic modeling, Parallel Machine, High Speed Machining*

1. Introduction

Parallel kinematic machines (PKM) are well known for their high structural rigidity, better payload-to-weight ratio, high dynamic performances and high accuracy [13, 14, 15].

High speed Machining (HSM) requires increasingly high dynamic performances on behalf of the machine tools. The principal projections concerning the structure and the components of the machine tools are the use of linear motors and the appearance of new architectures known as "parallel" [1]. A mechanism with parallel structure is a mechanism in closed kinematic chain whose final body is connected to the base by at least two independent kinematic chains [2]. In space, a rigid body can make translations along three mutually perpendicular axes and rotate about these axes as well. These independent motions constitute the six degrees of freedom (DOF) of the space. If some or all of these degrees of freedom of the rigid body are governed by a mechanical system with several degrees of freedom then this system is called a manipulator (robot). The first known industrial application of the parallel mechanisms is the platform of Gough [3]. Parallel mechanical architectures were first introduced in tire testing by Gough, and later were used by Stewart as motion simulators. An exhaustive enumeration of parallel robots' mechanical architectures and their versatile applications were described in [12] Intended for the test of tires. At the end of the Sixties, D. Stewart will re-use this architecture to design a flight simulator [4,5]. Versions 3 axes of the hexaglide were proposed thereafter with Triaglide (Mikron), Linapod (ISW Uni Stuttgart), Quickstep (Krause & Mauser) and Uran SX (Renault-Automation). These machines take again in fact an architecture already suggested in robotics with for example the "linear Delta" [6] and the "There-Star" [7] making it possible to maintain an orientation fixed of the tool.

Most of the existing PKM can be classified into two main families. The PKM of the first family have fixed foot points and variable–length struts, while the PKM of the second family have fixed length struts with moveable foot points gliding on fixed linear joints [17, 18].

Many three-axis translational PKMs belong to this second family and use architecture close to the linear Delta robot originally designed by Clavel for pick-and-place operations [16], and in the parallel module of the URAN SX machine. The kinematic modeling of these PKMs must be done case by case according to their structure.
Many researchers have contributed to the study of the kinematics of lower-DOF PKMs. Many of them have

focused on the discussion of both analytical and numerical methods [19, 20].
This paper investigates the position and orientation of a trajectory frame with respect to the fixed frame of the URAN SX machine.

2. Presentation of machine URAN SX

URAN SX is a horizontal pin machine tool dedicated to the operations of drilling, facing, tapping and boring, with parallel structure of Delta type (Figure 1), what confers to him dynamic performances much higher (about 30%) than those of the structures traditional series [8]. Its speed of pin is of 40000 tr/min, the use of linear motors authorizes accelerations going from (35- 50 m/s2). And the speeds displacement of the axes (100- 150 m/s).

Fig. 1 The machine URAN SX

3. Principle of the structure of the machine URAN SX

Basic architecture consists of a frame tunnel (Figure 2) cast solid rigid in which are laid out the three parallel axes of displacement, also distributed. The axes of motion are guided by roller slides with recirculation and are motorized by linear motors. The displacement of the axes by linear motors authorizes raised the speeds displacement, with important accelerations. These axes allow displacement and positioning in the three space plans of electro-stitches at very high speed adapted to machining VHS (Very High speed).

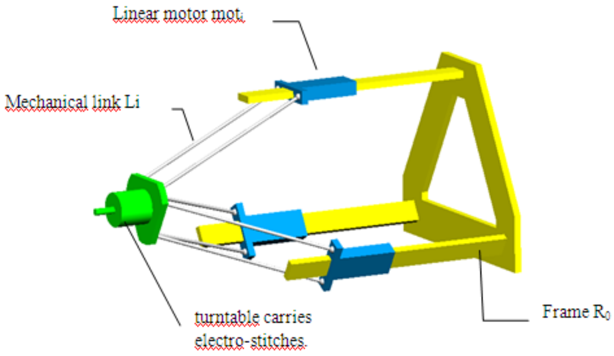

Fig. 2 CAD of the machine URAN SX

4. Parameter setting of URAN SX

The studied mechanism comprising a fixed part connected to a moving part “nacelle” by several mechanical link. The mechanical link is parts connecting the nacelle to the actuators. For a fitting of the Delta type, these mechanical link are gathered per pairs.

The distances from the various points Ai Have with the axis $\left(O_0, \overrightarrow{z_0}\right)$ are equal between them and constant $\forall t$.

By construction, one has $\left|\overrightarrow{A_1A_2}\right| = \left|\overrightarrow{A_3A_4}\right| = \left|\overrightarrow{A_5A_6}\right|$

In the same way, for any configuration, there are the equalities:

$\overrightarrow{A_1A_2} = \overrightarrow{B_1B_2}$; $\overrightarrow{A_3A_4} = \overrightarrow{B_3B_4}$; $\overrightarrow{A_5A_6} = \overrightarrow{B_5B_6}$

The parameter setting of the mechanism represented on Figure 4, the motors of axes are bound by slides to the frame R_0 , of axis parallel with z_0 . The bars b_i , $i \in [1,...,6]$, are of the same length and of ends A_i and B_i . They are bound by kneecaps as well to the motor of axes mot_j as to the turntable carries electro-stitches.

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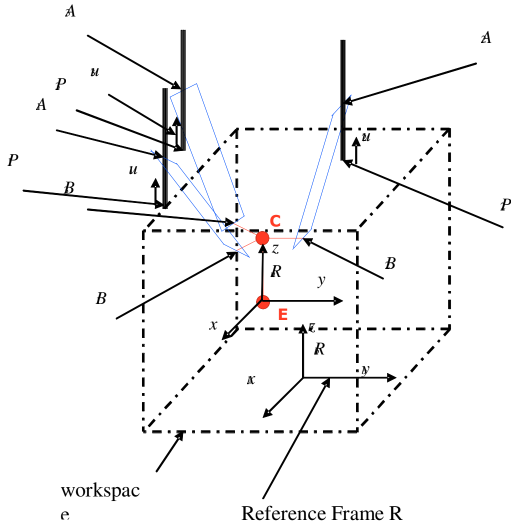

Fig. 3 Parameter setting of the mechanism

5. The kinematic diagram

The kinematic diagram very practical to represent the fitting of the various connections composing a mechanism, are of easy reading for the plane mechanisms and the simple space mechanisms, but quickly become illegible for the complex space mechanisms

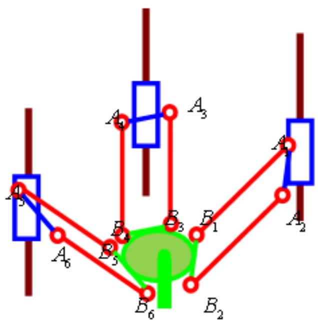

Fig. 4 Kinematic diagram

6. Graph of fitting

These graphs were proposed by François Pierrot in reference [10].

 Revolute joint (rotoide)

 Prismatic joint (slide)

 Ball-and-socket joint (rotile)

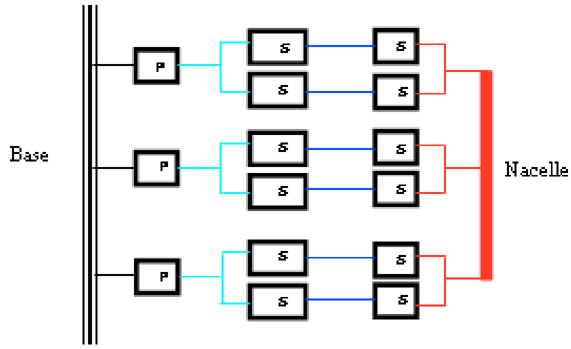

Fig. 5 Graph of fitting

7. Formulate of Grübler

The formula of Grübler gives the mobility of a mechanism in the general case, apart from the positions and of the singular fittings [11].

$$m = 6\left(N_p - N_i - 1\right) + \sum_{i=1}^{N_i} dof_i - m_{\text{int}} \quad (1)$$

m is the number of degrees of freedom of the mechanism.

N_p the number of independent solids (built excluded) $N_p = 11$

N_i the number of connections between these solids $N_i = 15$, 12 connections Spherical (kneecap) and 3 connections Prismatic (slide).

dof_i the number of degrees of freedom of the connection number i.

$$dof_i = (12\times3)+(3\times1) = 39$$

m_{int} is the number of internal mobility $m_{\text{int}} = 6$.

The mobility of this mechanism:

$$m = 6(11-15-1)+39-6 \Rightarrow m = 3$$

8. Geometrical models

Geometrical modeling with for goal to determine the system of equations connects the position and the orientation of the nacelle to the position of the actuators.

The parameter setting of this fitting is presented on the figures 6 and 7.

The slides are laid out parallel with the axis Z with a distance "D". The angular spacing of the slides is 120 degrees.

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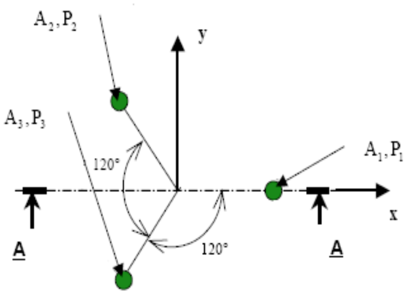

Fig. 6 Parameters setting of the base

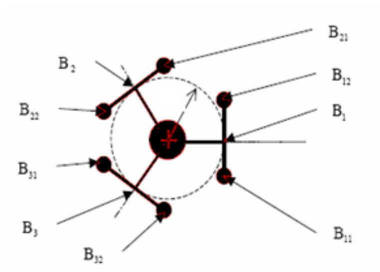

Fig. 7 Parameters setting of the nacelle

Coordinates of the points A_i in the reference frame related to the base R_b :

$$A_1=\begin{pmatrix} D \\ 0 \\ 0 \end{pmatrix} \quad A_2=\begin{pmatrix} -\frac{D}{2} \\ \frac{\sqrt{3}}{2}D \\ 0 \end{pmatrix} \quad A_3=\begin{pmatrix} -\frac{D}{2} \\ -\frac{\sqrt{3}}{2}D \\ 0 \end{pmatrix}$$

Coordinates of the points P_i in the reference frame related to the base R_b :

$$P_2=\begin{pmatrix} D \\ 0 \\ 0 \end{pmatrix} \quad P_2=\begin{pmatrix} -\frac{D}{2} \\ \frac{\sqrt{3}}{2}D \\ 0 \end{pmatrix} \quad P_3=\begin{pmatrix} -\frac{D}{2} \\ -\frac{\sqrt{3}}{2}D \\ 0 \end{pmatrix}$$

Coordinates of the points B_i in the reference frame related to the mobile platform R_n :

$$B_1=\begin{pmatrix} d \\ 0 \\ 0 \end{pmatrix} \quad B_2=\begin{pmatrix} -\frac{d}{2} \\ \frac{\sqrt{3}}{2}d \\ 0 \end{pmatrix} \quad B_3=\begin{pmatrix} -\frac{d}{2} \\ -\frac{\sqrt{3}}{2}d \\ 0 \end{pmatrix}$$

Components of the vectors in the reference frame related to the base:

$$u_1=\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad u_2=\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad u_3=\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

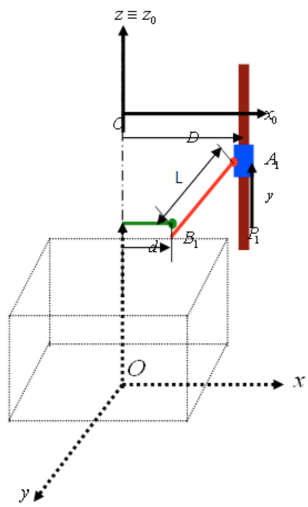

Fig. 8 geometrical Parameters setting

$$A_1B_1=(X-P_1)-(q_1u_1)$$
(2)

For the mechanical link bars languor is constant:

$$A_1B_1=l_1=L$$

$$[A_1B_1]^2=[(X-P_1)-(q_1u_1)]^2 \tag{3}$$

The geometrical model is given by the system made up of the three equations for $1 \le i \le 3$.

$$q_i^2-q_i\left[2(X-P_iB_i)u_i\right]+\left[(X-P_iB_i)^2-L^2\right]=0 \tag{4}$$

To solve this polynomial the determinant Δ should be calculated:

$$\Delta=\left[(X-P_iB_i)u_i\right]^2-\left[(X-P_iB_i)^2-L_i^2\right] \tag{5}$$

• For $\Delta<0$; then this polynomial has two combined complex solutions. In this case position X of the nacelle is not accessible.

• For $\Delta=0$; then this polynomial has a double real solution. In this case, the mechanism is in a singular position.

• For $\Delta>0$; then this polynomial has two distinct real solutions (regular position).

The first solution is given by the equation according to:

$$q_i=(X-P_iB_i)u_i-\sqrt{\left[(X-P_iB_i)u_i\right]^2-\left[(X-P_iB_i)^2-L_i^2\right]} \tag{6}$$

And the second solution is given by the equation according to:

$$q_i = (X - P_i B_i) u_i + \sqrt{\left[(X - P_i B_i) u_i\right]^2 - \left[(X - P_i B_i)^2 - L_i^2\right]} \quad (7)$$

The solution of the equation giving the greatest value of q_i is the second solution.

For $1 \le i \le 3$:

$$q_i = (X - P_i B_i) u_i + \sqrt{L_i^2 - \left[(X - P_i B_i) u_i\right]^2 - (X - P_i B_i)^2} \quad (8)$$

In coordinate them then points of each bar i in this equation replace we obtain the analytical expression of the opposite geometrical model:

$$\begin{cases} q_1 = z + \sqrt{L^2 - (d - D + x)^2 - y^2} \\ q_2 = z + \sqrt{L^2 - \left(\frac{1}{2}(D - d) + x\right)^2 - \left(\frac{\sqrt{3}}{2}(d - D) + y\right)^2} \\ q_3 = z + \sqrt{L^2 - \left(\frac{1}{2}(D - d) + x\right)^2 - \left(\frac{\sqrt{3}}{2}(D - d) + y\right)^2} \end{cases} \quad (9)$$

$$\begin{cases} z - q_1 + \sqrt{L^2 - (d - D + x)^2 - y^2} = 0 \\ z - q_2 + \sqrt{L^2 - \left(\frac{1}{2}(D - d) + x\right)^2 - \left(\frac{\sqrt{3}}{2}(d - D) + y\right)^2} = 0 \\ z - q_3 + \sqrt{L^2 - \left(\frac{1}{2}(D - d) + x\right)^2 - \left(\frac{\sqrt{3}}{2}(D - d) + y\right)^2} = 0 \end{cases} \quad (10)$$

$$\begin{cases} (z - q_1)^2 + L^2 - (d - D + x)^2 - y^2 = 0 \\ (z - q_2)^2 + L^2 - \left(\frac{1}{2}(D - d) + x\right)^2 - \left(\frac{\sqrt{3}}{2}(d - D) + y\right)^2 = 0 \\ (z - q_3)^2 + L^2 - \left(\frac{1}{2}(D - d) + x\right)^2 - \left(\frac{\sqrt{3}}{2}(D - d) + y\right)^2 = 0 \end{cases} \quad (11)$$

To obtain the analytical expression of the direct geometrical model, we must solve the system compared to variables x, y and z.

$$\begin{cases} (d - D + x)^2 + y^2 + (z - q_1)^2 = L^2 \\ \left(\frac{1}{2}(D - d) + x\right)^2 + \left(\frac{\sqrt{3}}{2}(d - D) + y\right)^2 + (z - q_2) = L^2 \\ \left(\frac{1}{2}(D - d) + x\right)^2 + \left(\frac{\sqrt{3}}{2}(D - d) + y\right)^2 + (z - q_3)^2 = L^2 \end{cases} \quad (12)$$

9. Models kinematics

The form of the matrices J_x and J_q of the kinematic model is:

$$J_x = \begin{bmatrix} (A_1B_1)_x & (A_1B_1)_y & (A_1B_1)_z \\ (A_2B_2)_x & (A_2B_2)_y & (A_2B_2)_z \\ (A_3B_3)_x & (A_3B_3)_y & (A_3B_3)_z \end{bmatrix} \quad (13)$$

$$J_x = \begin{bmatrix} d - D + x & \text{y} & \text{z-q}_1 \\ \frac{1}{2}(D - d) + x & \frac{\sqrt{3}}{2}(d - D) + y & \text{z-q}_2 \\ \frac{1}{2}(D - d) + x & \frac{\sqrt{3}}{2}(D - d) + y & \text{z-q}_3 \end{bmatrix}$$

$$J_q = \begin{bmatrix} A_1B_1u_1 & 0 & 0 \\ 0 & A_2B_2u_2 & 0 \\ 0 & 0 & A_3B_3u_3 \end{bmatrix} \quad (14)$$

10. The inverse kinematic model

The inverse kinematic model is the expression of $\dot{q}$ according to $\dot{x}$ the writing of the inverse kinematic model is:

$$\dot{q} = J_q^{-1} J_x \dot{x} \quad (15)$$

$$J = J_x^{-1} J_q \quad (16)$$

or J is called the matrix jacobienne.

11. Table of the values of position of the effecter and the actuators

For positions given in the workspace (x,y,z) the positions of the linear motors are calculated starting from analytical system of the geometrical model.

One applies the study of the machine URAN SX for following dimensions:

The slides are laid out parallel with the axis with a distance D=0.7m.

The nacelle has a distance d=0.15m to the axis Z.

The mechanical link is the two bars of a pair connecting the nacelle to the same actuator with a length L=1.3m replaces some in the system (13).

Calculation this fact for the positions of the final body following:

1st case. $(x_p = 0.250m, y_p = 0.250m, z_p = 0)$

2nd case. $(x_p = 0.250m, y_p = 0.250m, z_p = 0.250m)$

3rd case $(x_p = 0.250m, y_p = -0.250m, z_p = 0)$

4th case $(x_p = 0.250m, y_p = -0.250m, z_p = 0.250m)$

The results are the following:

Table 2: Analytical results.

L=1.3m, D=0.7m d=0.15m					
x m	y m	z m	q_1 m	q_2 m	q_3 m
0,25	0,25	0	1.24	1.1675	0.94173
0,25	0,25	0,25	1.49	1.1917	1.1917
0,25	-0,25	0	1.24	1.1675	1.1675
0,25	-0,25	0,25	1.49	1.4175	1.4175

These results represent the positions of the motors for each case of the positions of the tool in the workspace.

12. Graphs of the positions

12.1 Displacements of the linear motor q1 along axis Z for all the points of the plan (oxy) of the workspace, ($-0,25 \le x \le 0,25$ $-0,25 \le y \le 0,25$ $z = 0$) is given by the following graph

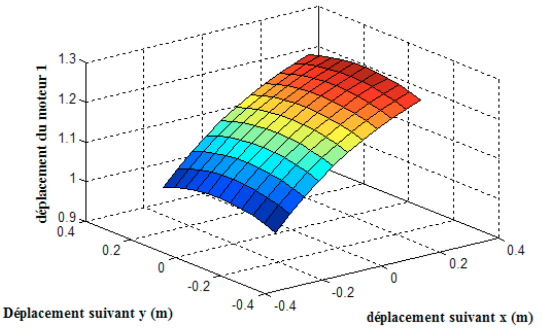

Fig. 9 Displacement of motor 1

12.2 Displacements of the linear motor q2 along axis Z for all the points of the plan (oxy) of the workspace, ($-0,25 \le x \le 0,25$ $-0,25 \le y \le 0,25$ $z = 0$) is given by the following graph

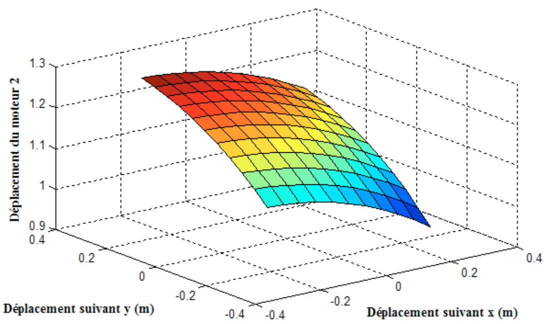

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Fig. 10 Displacement of motor 2

12.3 Displacements of the linear motor q3 along axis Z for all the points of the plan (oxy) of the workspace, ($-0,25 \le x \le 0,25$ $-0,25 \le y \le 0,25$ $z = 0$) is given by the following graph

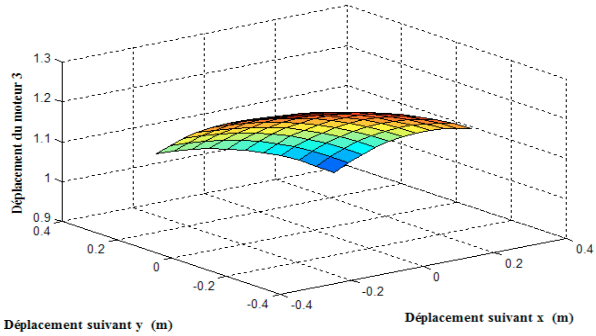

Fig. 11 Displacement of motor 3

13. Conclusion

The forward kinematics deals with the determination of the moving platform position as function of the joint coordinates.

We replace this variables of the workspace x, y and z in system (9) to obtain a the values of the joint coordinates q_i .

According to the results for each position (x, y, z) of the tool it there with several positions for the three linear motor.

The quality of the results obtained in this paper shows the need for geometrical modeling for the study, the ordering and the optimization of the parallel machine tools, geometrical modeling plays a very important role.

The matrix of Jacobienne transformation connected between variables of the workspace (Vectors of positions, speeds, and accelerations x, $\dot{x}$, $\ddot{x}$) and variables of articulair space (Vectors of positions, speeds and accelerations q, $\dot{q}$, $\ddot{q}$)

This modeling is the base of the kinematic, static study and dynamics of the parallel mechanisms.

Notations

m : Number of degrees of freedom of the mechanism.

N_p : Number of independent solids (built excluded),

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N_i : Number of connections between these solids,

dof_i : Number of degrees of freedom of the connection number i .

m_{int} : Number of internal mobility.

J : Jacobian matrix

Jx and Jq : two Jacobian sub-matrices

q : Joint vectors

$\dot{q}$: Joint velocities

x : Operational victors

$\dot{x}$: Operational velocities

(x,y,z) : Positions of nacelle ,

D : Diameter of fixed base.

d : Diameter of moved base.

L : mechanical link languor.

R_b : Reference frame related to the base.

R_n : Reference frame related to the mobile platform.

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