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MACHINING PERFORMANCE OPTIMIZATION OF PARALLEL KINEMATIC MACHINES TOOLS WITH REGARD TO THEIR ANISOTROPIC BEHAVIOUR

Today, Parallel Kinematic Machines tools (PKMs) appear in automotive and aeronautic industries. These machines allow a benefit of productivity due to their higher kinematics performances than Serial Kinematic Machines tools (SKMs). However, their machining accuracy is lower. Moreover, the compensation of the defects which penalizes the machined parts quality is difficult due to their anisotropic behaviour. Thus, this article deals with the development of methods improving the machined parts quality and the productivity. In order to improve parts quality, the static behaviour of the machine structure is considered with a model taking into account joints and legs compliances. Then, it allows determining a static workspace. About the productivity, the improvement of kinematics performances is performed through an optimization work of the non productive tool path between cutting operations. The computed tool path must verify a minimum time constraint and avoid collisions between the tool and the machined part. All the methods are illustrated with the PKM Tripteor X7 developed by PCI.

1. INTRODUCTION

Today, few Parallel Kinematic Machines tools (PKMs) are used for High Speed Machining (HSM) tasks in the aeronautic or automotive industry [6],[19]. However these machines have a higher dynamic potential than Serial Kinematic Machines tools (SKMs) thanks to their lower moving masses. This property allows having a better productivity [17]. Nevertheless, PKMs have a low level of accuracy compared to SKMs. Indeed, the tool pose quality and the mechanical behaviour of the machine tool structure (geometric, static or dynamic) have a direct influence on the machined part quality [13].

A particularity of PKMs is their anisotropic and variable behaviour in the cartesian workspace. Thus the pose of the part has an influence on the machined quality. Therefore, a workspace where the machine behaviour allows machining the part with the adapted

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quality and production time must be defined. This optimal workspace is the intersection of three workspaces: a geometric workspace, a dynamic workspace and a kinematic workspace [3].

To improve accuracy level of PKMs, the structure influence on the machined part quality must be predicted. Thus, static and geometrical behaviour of the machine tool have to be controlled in order to improve the machined part quality. The geometrical behaviour is influenced by the definition of the Inverse Kinematics Model (IKM) and its parameters identification method [3]. The static modelling has to be developed as a compact and predictable model in order to compute the tool pose defects due to the compliance of the legs and the joints along the tool path.

About the productivity, the structure of PKMs induces a variable gain of tool feed-rate [18]. Therefore the tool path has to be optimized in order to take into account this behaviour [8]. However, some machining operation, like drilling of preformed parts, have a non effective cutting times including rapid motion between cuts which can be very important (more than 60% of the manufacturing time) [19]. Thus it can be relevant to optimize these trajectories between cuts to increase the productivity.

In this article, two research ways to improve the machining with PKMs are presented. The first one ensures to develop a static modelling which take into account legs and joints compliance. The second one is based on the optimization of non productive tool paths in order to improve the productivity. The developed methods are then applied on the Tripteor X7 machine tool.

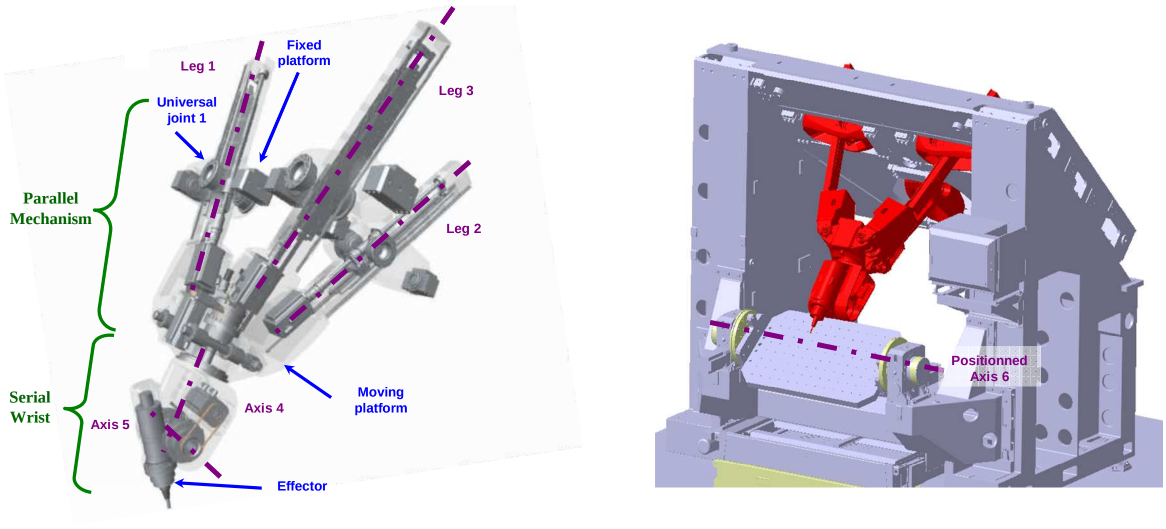
After a brief presentation of the Tripteor X7, its complete inverse and forward kinematic models are proposed. Thus, the developed IKM is used to define a static model of the machine where joints and legs compliance are taken into account. Finally, an optimization method of trajectories between cuts is developed in order to improve the productivity.

2. PRESENTATION OF THE TRIPTEOR

PKMs designed until now have a lower rigidity than SKMs. Most of them use an hybrid robot architecture, like the well-known Tricept architecture, to improve the tool accessibility relative to the machined part. That is why Neumann designs a new architecture of PKM called Exechon. This structure is overconstrained in order to increase its stiffness [9]. The Exechon architecture is currently used by PCI at Saint Etienne for producing Tripteor X7 machines tools.

The Tripteor X7 is a hybrid PKM with five axis. A parallel mechanism provides three degrees of freedom and a serial wrist two rotational degrees of freedom. In order to improve the tool accessibility around the part, PCI has added a sixth positioned axis which allows a rotation of the table around $\vec{x}$ axis of the machine. Fig. 1 presents the Exechon architecture (A) and the complete machine tool Tripteor X7 (B).

To develop methods improving accuracy and productivity of the Tripteor, its inverse and forward kinematic model had to be determined.



-A- Exechon robot -B- Tripteor machine tool

Fig. 1. Presentation of the Tripteor machine tool

3. INVERSE AND FORWARD KINEMATIC MODEL OF THE TRIPTEOR

The Inverse Kinematic Model (IKM) and Forward Kinematic Model (FKM) are used in the Numerical Control (NC) of the machine.

The IKM consists in computing joint workspace coordinates (q_1, q_2, q_3, q_4, q_5) with regard to the cartesian workspace coordinates (X_{TCP}, Y_{TCP}, Z_{TCP}, i, j, k) [11]. The IKM of Tripteor X7 parallel unit is developed by Puchtler [14]. Thus, this section details the complete IKM of Tripteor X7.

In order to develop this IKM, some coordinate systems are defined on the machine geometry (Fig. 2-A-). Thus the Internal Coordinate System (ICS) is linked to the fixed platform of the robot, the Mobile Platform System (MPS) is linked to the mobile platform, the Based Cartesian System (BCS) is linked to the machine tool and the Tool Center Point system (TCP) is linked to the effector. In order to respect the design of the Tripteor X7, the developed model takes into account some geometric constraints and parameters [14], [16]. Thus, six equations can be defined (system (1) and (2)).

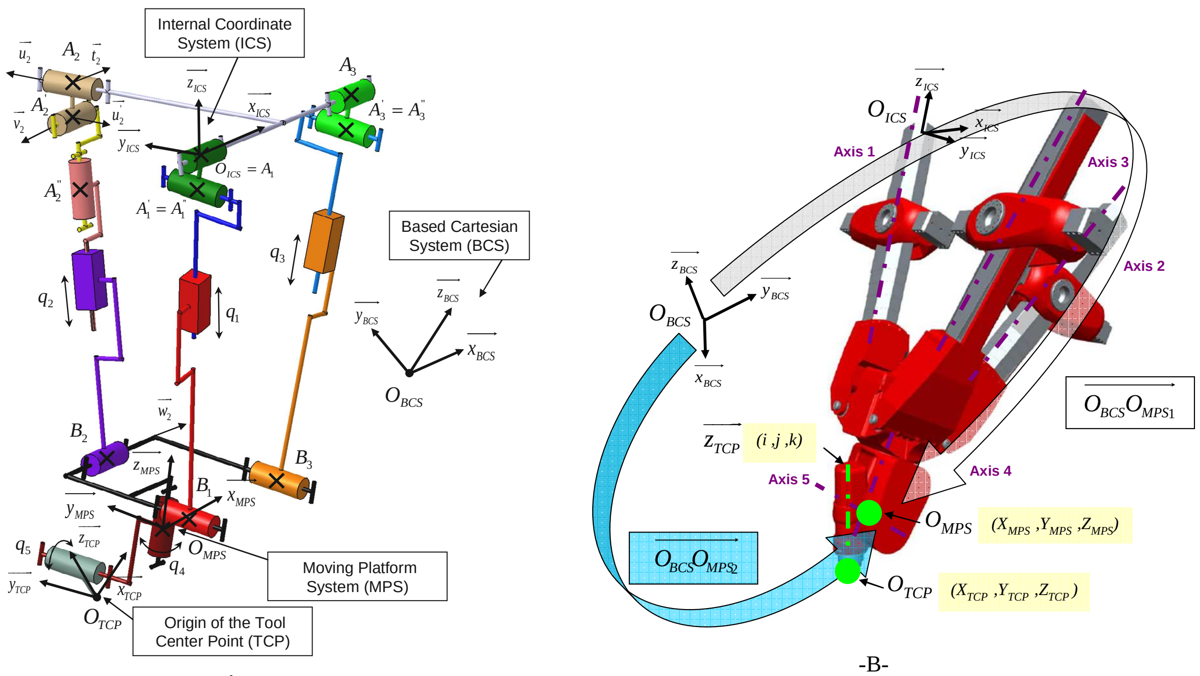
However, there are no analytical solutions for this problem. Indeed, the systems (1) and (2) have non linear equations [14]. That is why the computation is realized numerically by applying a Newton-Raphson algorithm.

$$\begin{cases} \overrightarrow{A_2''B_2}.\overrightarrow{w_2} = 0 \\ \overrightarrow{A_2''B_2}.\overrightarrow{u_2'} = 0 \\ \overrightarrow{A_2''B_2}.\overrightarrow{v_2} = 0 \end{cases} \quad (1) \quad \& \quad \begin{cases} (\overrightarrow{O_{BCS}O_{MPS2}} - \overrightarrow{O_{BCS}O_{MPS1}}).\overrightarrow{x_{BCS}} = 0 \\ (\overrightarrow{O_{BCS}O_{MPS2}} - \overrightarrow{O_{BCS}O_{MPS1}}).\overrightarrow{y_{BCS}} = 0 \\ (\overrightarrow{O_{BCS}O_{MPS2}} - \overrightarrow{O_{BCS}O_{MPS1}}).\overrightarrow{z_{BCS}} = 0 \end{cases} \quad (2)$$

Where:

- $\overrightarrow{w_2}$ is the unit director vector of the rotation axis between mobile platform and leg 2.
- $\overrightarrow{u_2'}$ is the unit director vector normal to the rotation axis between universal joint 2 and leg 2.

- $\overrightarrow{v_2}$ is the unit director vector of the rotation axis between universal joint 2 and leg 2.
- $\overrightarrow{A_2^{"}B_2}$ is the vector between the two ends of leg 2.



-A- -B-

Fig. 2. Kinematic diagram of Exechon architecture (A) and chains vectors used for the resolution of IKM (B)

The vector $\overrightarrow{O_{BCS}O_{MPS}}$ can be explained with two differents ways. The first one is represented in white in the Fig. 2-B- and contains the O_{ICS} point. The second one is represented in grey and includes the O_{TCP} point.

The minimization of these equations gives the value of an intermediate set of parameters (X_{MPS}, Y_{MPS}, Z_{MPS}, β, θ_2, et θ'_2), with X_{MPS}, Y_{MPS}, Z_{MPS}, the coordinates of the point O_{MPS} in ICS, β the rotation angle of the mobile platform around $\overrightarrow{y_{ICS}}$, θ_2 the rotation angle between universal joint 2 and the fixed platform around $\overrightarrow{u_2}$ and θ'_2 the rotation angle between leg 2 and universal joint 2 around $\overrightarrow{t_2}$ (Fig. 2 -A-).

Another intermediate parameter α, is the rotation angle of the moving platform around $\overrightarrow{x_{ICS}}$. This parameter is determined analytically and is given by the following expression:

$$\alpha = \arctan\left(\frac{-Z_{MPS}.Y_{B1} + Y_{MPS}.\sqrt{Y_{MPS}^2 + Z_{MPS}^2 - Y_{B1}^2}}{-Y_{MPS}.Y_{B1} - Z_{MPS}.\sqrt{Y_{MPS}^2 + Z_{MPS}^2 - Y_{B1}^2}}\right) \quad (2)$$

where Y_{B1} is the component of the $B1$ point along $\overrightarrow{y_{MPS}}$ axis.

Finally, (q_4, q_5) are determined in function of (X_{MPS}, Y_{MPS}, Z_{MPS}, β, θ_2, and θ'_2) and α by solving the system:

$$\left\{\overrightarrow{V}\right\} = \begin{Bmatrix} \sin(q_4)\times\sin(q_5) \\ -\sin(q_4)\times\cos(q_5) \\ \cos(q_5) \end{Bmatrix} \tag{3}$$

where $\left\{\overrightarrow{V}\right\}$ is a vector, the components of which are function of (X_{MPS}, Y_{MPS}, Z_{MPS}, β, θ_2, and $\theta'_{2'}$) and α.

(q_1, q_2, q_3) are determined in function of X_{MPS}, Y_{MPS}, Z_{MPS}, β, θ_2, and $\theta'_{2'}$) and α by using Merlet's method [11]. It consists in expressing the length of vectors $\overrightarrow{A_i^{"}B_i}$.

$$\text{For } i\in[1,3],\ \left\|\overrightarrow{A_i^{"}B_i}\right\| = \sqrt{(\overrightarrow{A_i^{"}A_i^{'}} + \overrightarrow{A_i^{'}A_i} + \overrightarrow{A_i O_{ICS}} + \overrightarrow{O_{ICS}O_{BCS}} + \overrightarrow{O_{BCS}O_{MPS}} + \overrightarrow{O_{MPS}B_i})^2} \tag{4}$$

Then, the relation between (X_{MPS}, Y_{MPS}, Z_{MPS}, β, θ_2, and $\theta'_{2'}$) and (q_1, q_2, q_3, q_4, q_5) is determined and the IKM is defined. To reduce the transformation errors, an identification of the geometrical parameters is realized [3].

The FKM consists in computing cartesian workspace coordinates (X_{TCP}, Y_{TCP}, Z_{TCP}, *i, j, k)* depending on the joint workspace coordinates (q_1, q_2, q_3, q_4, q_5) [11]. It is defined by using the optimization method developed for the IKM. The equations to minimize are:

$$\begin{cases} \overrightarrow{A_2^{"}B_2}.\overrightarrow{w_2} = 0 \\ \overrightarrow{A_2^{"}B_2}.\overrightarrow{u_2^{'}} = 0 \\ \overrightarrow{A_2^{"}B_2}.\overrightarrow{v_2} = 0 \end{cases} \quad (5) \qquad \& \qquad \begin{cases} q_1 - q_{1-computed} = 0 \\ q_2 - q_{2-computed} = 0 \\ q_3 - q_{3-computed} = 0 \end{cases} \quad (6)$$

where $q_{i\text{-}computed}$ are values computed for each set of optimization loop.

The definition of these two models is necessary to optimize the machining behaviour. Indeed, the part is produced in the cartesian coordinate system and the machine is controlled on the joint coordinate system.

4. STATIC MODELLING OF TRIPTEOR X7

A predictive model of Tripteor X7 static behaviour is presented in this section. The proposed model takes into account the non linear behaviour of the joints and the couplings between the degrees of freedom in the joints. Indeed, the joints used in this architecture (revolute joints with rolling elements) have a non linear behaviour and present couplings [2]. However, these joints are generally modelled by a spring with a constant stiffness [4], [10]. This hypothesis does not represent correctly the behaviour of joints realized with rolling elements [2].

First, the models of joints retained are presented. Then, the complete model of the Tripteor X7 parallel unit is proposed. Finally, the method used to compute the displacements of the mobile platform is explained.

4.1. TECHNICAL ANALYSIS OF THE JOINTS

Two kinds of revolute joints are used in the Tripteor X7. The first one is composed of roller bearings and is used in universal joints between the base platform and the legs. In the second one, angular ball bearings are used. These joints are located between the legs and the mobile platform.

Many bearings models are found in literature [2]. Some of them, as Palmgren or Krämer models, consider that the stiffness in each direction is independent. Others take into account the couplings between the different degrees of freedom, the gyroscopic effects and the deformations of the housing. In our model, a modelling method using 3x3 matrix proposed by Hernot is used [6]. This model enables the determination of bearings inner ring displacements (axial and radial). In addition, it takes into account the coupling between these displacements. This model is easily adaptable to assemblies with two or more roller bearings or angular contact ball bearings. Nevertheless, this model does not consider the gyroscopic effects and the deformations of the housing. The gyroscopic effects are negligible in the studied architecture as the bearing assemblies are found in passive joints where angular velocities are relatively low. The housing deformations are neglected before legs deflections, which are considered in the proposed model.

4.2. LEGS MODELLING

The Tripteor X7 architecture is overconstrained. Thus, the determination of the efforts in the legs is more complex than with an isostatic mechanism. Static analysis of the mechanism shows that the legs are stressed in traction-compression, bending and torsion.

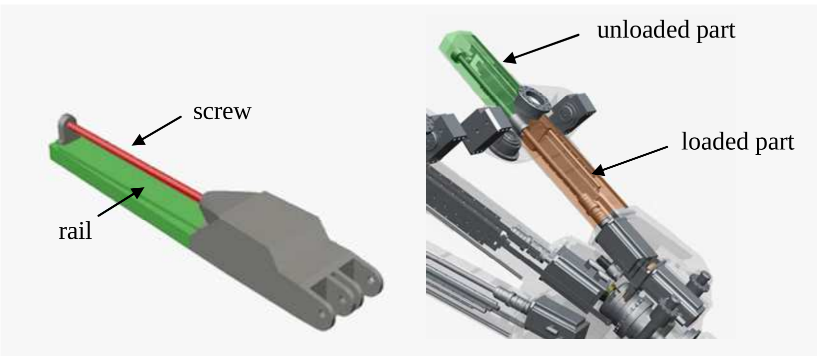


Fig. 3. Geometry of a leg

Thus, all the efforts in the direction of the leg are supported by the screw. In torsion and bending, the efforts are mainly transmitted by the rail (Fig. 3).

To simplify the leg model, only the rail is supposed to be stressed in bending and torsion. Finally, the leg is modelled by two beams with Euler-Bernoulli hypotheses:

- one for the screw, stressed only in traction-compression.

- one for the rail, stressed in bending and torsion.

The lengths of those two beams are variable, depending on the platform position in the workspace.

The proposed model takes into account joint and leg flexibilities. The contributions of these two sources of deflections are added to determine the behaviour of the machine.

4.3. COMPLETE MODEL OF TRIPTEOR X7 MACHINE TOOL

In the present section, the complete model of Tripteor X7 is developed. Energetic methods are used to compute the displacements of the mobile platform under given loads. The use of energetic methods enables the rapid addition of each element contribution in strain energy, which in this case are joint and leg deflections.

Two overconstrained parameters are chosen: Mz_{01} and Mz_{03}. They represent the moments in leg 1 and 3 universal joints between the legs and the fixed platform (Fig. 3).

Thus the strain energy of the whole structure can be expressed in function of these two parameters by:

$$E_D(Mz_{01}, Mz_{03}) = \frac{1}{2}\sum_{i=0}^{3}\left\{\int_0^{q_i}\left(\frac{N_i^2}{ES} + \frac{Mf_{xi}^2}{EI_{Gx}} + \frac{Mf_{yi}^2}{EI_{Gy}} + \frac{Mt_i^2}{GI_0}\right).ds + F_{ui}^T K_{sui}^{-1} F_{ui} + F_{ri}^T K_{sri}^{-1} F_{ri}\right\} \tag{7}$$

where:

- q_i is the length of leg i, which is equal to the length of the part of the screw that is loaded.
- s is the curvilinear abscissa along the screw.
- N_i is the compression (or tensile) force in leg i screw.
- M_{fxi} and M_{fyi} are the x and y components of the bending moments in leg i.
- M_{ti} is the torsional moment in leg i.
- E is the Young modulus of the screw.
- G is the shear modulus.
- S is the section of the screw.
- I_{Gy} and I_{Gz} are the moments of inertia of the rail about axis $\vec{y}$ and $\vec{z}$.
- I_0 is the polar moment of inertia of the rail.
- K_{sui} is the stiffness matrix of the bearing assemblies in leg i universal joint.
- F_{ui} is the effort supported by leg i universal joint.
- K_{sri} is the stiffness matrix of the bearing assembly in leg i revolute joint.
- F_{ri} is the effort supported by leg i revolute joint.

More details about the computing method and the parameters used are provided in [1].

The IKM developed in part 0 is used here to compute q_1, q_2 and q_3 in order to determine the stiffness of the machine in the whole workspace.

The overconstrained parameters are determined by numerically minimizing E_D, for each pose of the mobile platform.

After determining these two parameters Mz_{01} and Mz_{03}, the displacements of the mobile platform are easily computable by applying Castigliano's theorem. For example, with an effort F_{ex} applied in $\vec{x}$ direction, the displacement δ_x of the mobile platform is given by the expression:

$$\delta_x = \frac{\partial E_D}{\partial F_{ex}} \tag{8}$$

The displacements can be computed for any given load applied on the mobile platform. The displacements obtained for a 1000N load applied on the mobile platform at a given z altitude is presented in Fig. 4. This figure shows the anisotropic behaviour of this machine and the importance of part positioning in order to remain in the areas which allow respecting the quality of the parts.

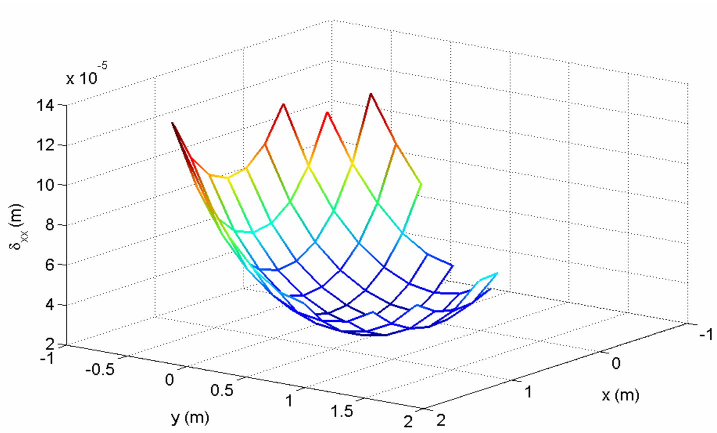


Fig. 4. Displacements along $\vec{x}$ for an effort in $\vec{x}$ direction and z=*-1m*

These studies ensure to define a relevant part pose with regard to the tool path and to the static behaviour. To improve the machining, when the wanted machining accuracy is attempted, the machining time must be reduced.

5. OPTIMIZATION OF TOOL PATHS BETWEEN CUTS

The anisotropic and variable kinematic behaviour of PKMs in the cartesian workspace require to realised a dedicated study in order to have better kinematic performances than SKMs. Several authors have already developed methods to reduce machining time by modifying the shape of productive tool paths [8]. The work presented in this paragraph is focused on the modification of non productive tool paths between cuts in order to minimize machining time.

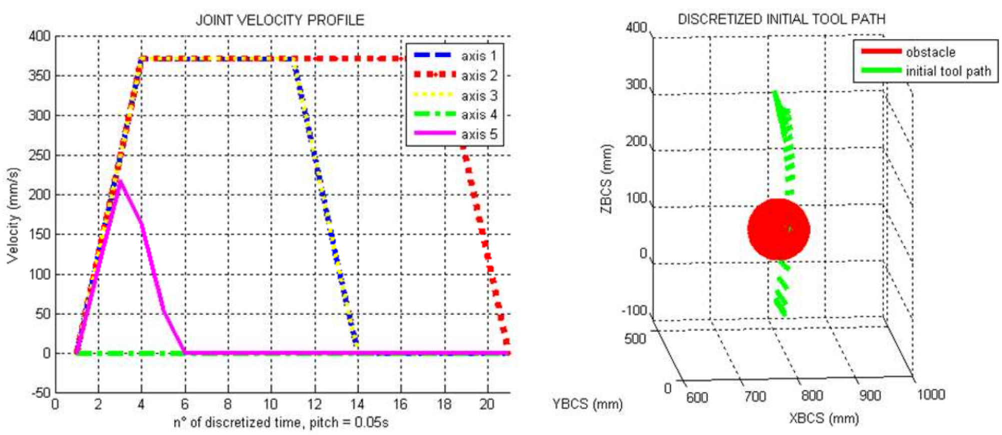
These tool paths are usually built with a Computer Aided Machining (CAM) process by using straight and circular trajectories in the cartesian workspace. But these tool paths are not optimal for the productivity because their length is not minimal and they are not C^2 continuous [12]. Therefore, a method that determines the fastest tool path between two imposed tool configurations (position and orientation) by avoiding collisions between tool and obstacles in the workspace is developed (Fig. 7 -A-).

To realize this computation, two optimization methods are available. The first one consists in building an initial tool path that avoids collisions but does not minimize the displacement time. The optimization must minimize this time while respecting the non collision constraints [15], [7]. The second one is to propose an initial tool path that minimizes the displacement time but does not avoid collisions. The optimization has to minimize collisions while respecting the displacement time given by the initial tool path. In our work, this method is chosen and it allows computing an initial solution easily. However, this method only gives an acceptable solution if collisions are avoided. Next paragraph defines the optimization method.

5.1. OPTIMIZATION METHOD DEFINITION

To define the optimized tool path, a constrained optimization, which is the *fmincon* function in Matlab, is used. This function uses a Newton-Raphson algorithm. The optimized parameters are the joint velocities. Thus, V_i^k is the axis i velocity at the k^{th} discretization point of the tool path.

The initial set of parameters is easily built by loading each axis maximally with respect to its kinematic limits of position (joint limits), velocity and acceleration. Each axis must have a null initial and final velocity and it must reach the position corresponding to the final imposed tool pose. The initial profile of joint velocities is the fastest (Fig. 5 -A-). It does not necessary respect non collision constraint between the tool and the part (Fig. 5 -B-).



-A- Joint velocity initial profile

-B- Initial tool path in the cartesian workspace

Fig. 5. Initial solution of optimization problem

The slowest axis to reach its final position is called the “limiting axis” and gives the optimal time of the displacement t_d.

Constraints imposed on the optimization computing are the kinematic limits of the axis and the constraint of displacement time t_d. The constraint of no collision is taken into account in a cost function f_{cost}. For that, tool and part geometries are represented by spheres [15]. Thus, the distance between the tool and the part is easily expressed in the cartesian workspace by:

$$d = \sqrt{(Xto - Xob)^2 + (Yto - Yob)^2 + (Zto - Zob)^2} - Rto - Rob \tag{9}$$

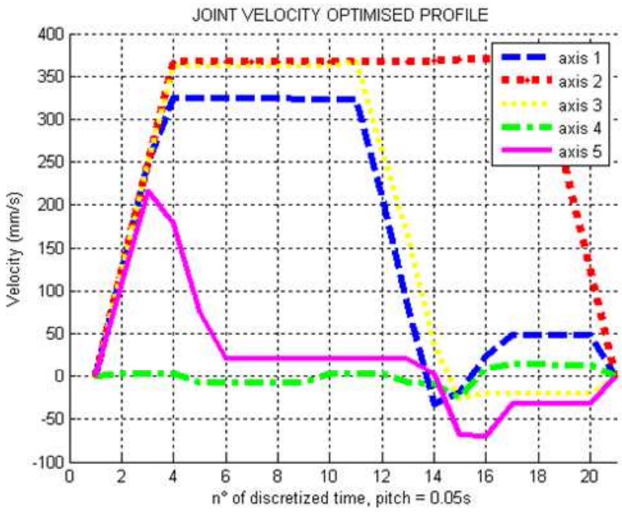
where *Xto*, *Yto*, *Zto* are the coordinates of the tool sphere centre in the cartesian workspace; *Xob*, *Yob*, *Zob* are the coordinates of the part sphere centre, *Rto* the tool spheres radii and *Rob* the part sphere radii. Thus, collisions cases are reflected by a negative value of *d*. *Xto*, *Yto* and *Zto* are computed in function of optimization parameters by using the FKM. Then, the cost function f_{cost} is obtained as the sum of all the negative values of *d*:

$$f_{cost} = \sum (d < 0) \tag{10}$$

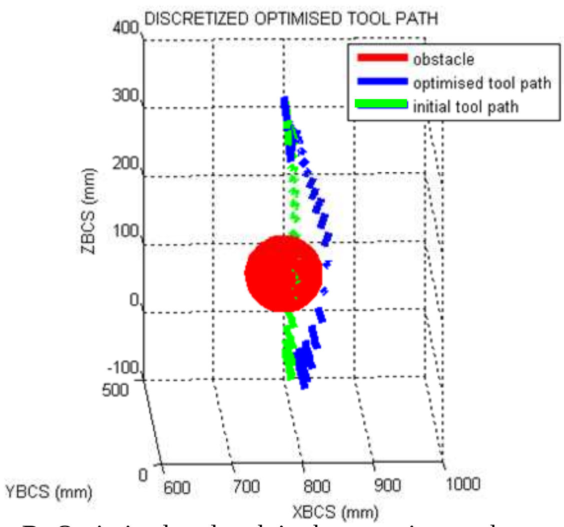
Thus, avoiding the collisions is equivalent to a null value of f_{cost}. Finally, the optimization only gives an acceptable tool path if the final value of f_{cost} is 0. If it does not, we have to begin a new optimization computing where the imposed displacement time t_d is increased.

5.2. ILLUSTRATION OF THE METHOD ON THE TRIPTEOR X7

We apply the presented method on the Tripteor X7 for the case described in Fig. 6. The computed optimal time is 1.05s. The computing time for this example is 3 hours. This time is function of the time pitch. Nevertheless, the accuracy of the final tool position is then linked to the time pitch. Indeed, the final position considered on the optimization is near the final imposed pose with a tolerance of one pitch. The time pitch value is 0.05s in this example.



-A- Joint velocity optimized profile



-B- Optimized tool path in the cartesian workspace

Fig. 6. Solution resulting of the optimization

Then, two tool paths resulting of the CAM and of the optimization have been tested on the Tripteor X7. Thus, the optimized tool path is 28% faster with a displacement time of 1.78s instead of 2.47s for the CAM tool path Fig. 7.

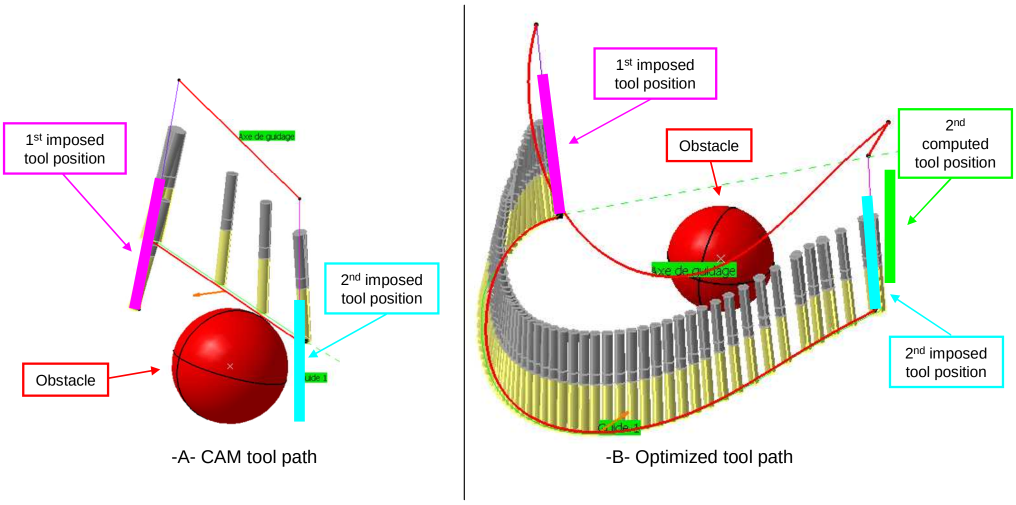


Fig. 7. Comparison between the two tool paths

In conclusion, this first work brings significant benefit, but it can be improved. Indeed, the axis jerk is not yet taken into account. Moreover, to increase the accuracy of the method, it would be interesting to approximate part geometry by an inclusive box which makes the collision detection more complex.

6. CONCLUSION AND PROSPECTS

This article studies the behaviour of a new Parallel Kinematic Machine tool: the Tripteor X7 by PCI. Some research ways are presented in order to improve the consistency of the couple machine/part. These ways lead to define models or methods dedicated to a type of machine tool structure and to a given part to be machined. Thus, in this study, the machine structure is the Exechon robot and the machined parts are preformed parts requiring drilling operations essentially. After the definition of the Inverse and Forward Kinematic Models, a predictive static model is computed in order to minimize defects on the parts by positioning the machined part in a particular workspace. Finally, a computation method of tool paths between cuts is presented in order to increase the productivity.

A main perspective of this work is to adapt these models and methods for structural machined parts where cutting forces are higher and more complex. Indeed, the Tripteor X7 has a higher stiffness level than other PKMs. That is why it should be particularly adapted to these machining. Thus, the creation of a dynamic model taking into account inertial effects and the determination of adapted machining operations could be of high interest.

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- modelling of the manufacturing process;
- virtual machining;
- emergence of new manufacturing methods.

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