Optimal Design of a 6-dof Parallel Measurement Mechanism Integrated in a 3-dof Parallel Machine-Tool

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***Abstract*— This paper presents the design and the optimization of a parallel machine-tool composed of (i) an actuated parallel 3-dof mechanism (a linear Delta) and (ii) a measuring 6-dof mechanism (a Gough platform)). The interest to use a measuring device independent of the actuation device is shown and the modeling of both devices used for the optimization is explained. Then, the optimization is presented; it is performed to obtain the best resolution for the measuring system evaluated at the tool level.**

I. INTRODUCTION

Machine-tool (MT) builders are always looking for better performances in terms of accuracy, speed and stiffness. Naturally, machine-tool designers took their inspiration from recent advances in robot kinematic architectures, in particular Parallel Kinematics Machines (PKMs) [1] [2] [3] [4]. PKMs have nowadays shown their efficiency in some robotic domains and commercial robots are widely available today [5].

Among the transfers from well known robotic PKMs to the machine tool industry, one can cite:

- The hexapods, where six variable length struts link a moving traveling plate to a base. The first built PKM belonging to this family was proposed by Gough [6], and the first machine tool inspired by this kinematics was the Variax [7]. Until today, a lot of prototypes are built:
  - The Hexapode 300 of the company CMW,
  - The Ingersoll H0H600 machine-tool,
  - The Mikromat 6X Hexapod,
  - The Toyoda HexaM [8]...
- The Delta kinematics invented by prof Clavel [9] is lower mobility PKM (displacements of the traveling plate are restricted to three translations). It is a light weight structure having intrinsically high dynamic performances. Robots based on this kinematics are widely available (see, for example ABB flexpicker). Machine-tools prototypes were also designed: UraneSX [10] that can reach up to 4g in its workspace or Krause Quickstep [11].

Whatever the kinematics is, calibration is required to get the best of the performances of a given mechanical architecture. To guarantee optimal performances of the machine during its life-cycle, a machine needs to be re-calibrated. This is a non-productive phase of machine life-cycle that affects its availability for machining.

Moreover, some errors due to elasticity of machine elements, hysteresis or backlashes are very difficult to model and to identify [12] [13].

Indeed, the basic problem in machining is to impose accurate tool positioning regarding the part to be machined. The calibration tries to identify model parameters that reduce the positioning error of the tool. Once these parameters are identified, the model runs "open loop", ie machine behavior is expected to be the one that has been modeled and identified whatever the stress in machine components is.

For Cartesian classical machine tools, the identification can be done axis per axis. Parameter identification can be very accurate as the problem is decoupled. Identifying PKM parameters according to this principle is not possible as all axes are coupled in the model. A full calibration of the model must be done, but it always ends in a compromise between the number of parameters and the numerical stability.

The best way to deal with accuracy is to be always able to know the tool position accurately, ie with a quality as close as possible to a metrological one, assuming that the structure of the machine has not a metrological quality as it is subject to deformations under high stress in its components. One way to proceed is to use non-contact full pose measurement system, like vision system for example [14] [15]. But there is still ongoing research on this topic and, even if algorithms are available, they are not able today to guarantee the requested resolution on the whole workspace of the machine. Moreover, the refreshment rate is not high enough for the control loop, but it is still a promising way of research for the future.

Another possibility is to build a mechanical structure, with metrological considerations that is able to give information to compute the real tool pose.

This solution is the purpose of this paper and will be discussed in the following sections.

To prove the feasibility and the efficiency of this concept, a PKM MT architecture (Delta) must be firstly selected and then a measuring architecture (Gough platform) is defined. Justification, description and modeling are given in section II. As it is well known that behavior of PKMs depends strongly on their design parameters, an optimization for both mechanisms is done in section III. The results of this optimization and the corresponding design are shown in section IV while conclusion and future works are introduced in section V.

II. MACHINE DESCRIPTION

A. Selection of the architectures

1) Actuation architecture: Basic machining operations require three translational degrees of freedom (dof). We must select an architecture that provides these dof while constraining the three rotational dof to a constant value. Several hybrid mechanisms or PKMs are able to provide these dof [16]. Among them, one can cite:

- the Tsai mechanism [17],
- the Star mechanism [18],
- Speed-R-Man mechanism [19]...

The architecture that guarantees intrinsically the highest dynamic performances is the Delta. For MTs, linear actuation is preferred to make is as mechanically stiff as possible. So the traveling plate will be actuated by a linear delta, as in the UraneSX MT. The Delta architecture theoretically imposes a constant orientation of the traveling plate and allows controlling three translations. But due to manufacturing and assembly errors, elastic deformations of machine elements it is not possible to guarantee that no parasitic rotation of the platform occurs. These rotations impairs machine accuracy because of the varying lever arm (depends on tool length and position of tool cutting edge) between the tool extremity and the moving platform. The consequence is that the measuring device to be integrated to the machine must be able to measure the X, Y, Z position, but also the parasitic rotation to provide the ability for the control to compensate for all errors.

2) Measurement architecture: As mentioned before, a full pose measurement system is required. Non contact system based on vision are, today, not accurate enough and cannot guarantee a fast refresh rate compatible with control loops. Concerning the existing non contact measuring system based on laser (like laser tracker), they are too expensive and cannot measure the orientation of the measured object. We propose here to rely on a mechanical measuring system. A strong constraint on this measuring system is that it will be attached on one side to the fixed base of the machine and on the other side on the moving traveling plate. The problem is that the traveling plate is expected to move in machine workspace with a high acceleration capability. The measuring system must not reduce this acceleration capability. The consequence is that it must be light weight. But, this mechanical measuring device must not transmit any efforts to insure a good accuracy. The kinematics of the system must take account of it. Moreover collision considerations with the actuation architecture must be taken into consideration for avoiding any restriction of machine workspace.
Several architectures are available to measured orientation and positions: serial ones or parallel ones. Serial mechanical architectures are rejected because of their dynamics which are not good enough to follow the Delta displacement. On the other hand, a PKM measuring system can have the following advantages:

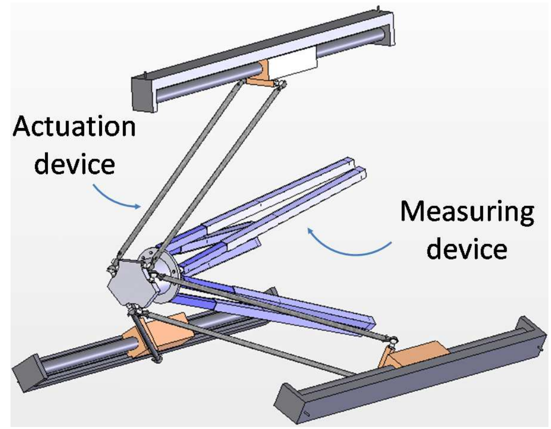


Fig. 1. Measuring device location

- Lightweight, so compatible with high accelerations
- Measure the orientation and the position of its end-effector
- Good resolution to detect small displacements...

The kinematics of the parallel measuring system must be chosen. First of all, only distance measurements are considered because it is easier to measure accurately a distance than an angle and the problem of lever arms is reduced. The simplest architecture, which can be used considering this, is the Gough platform. Moreover, this mechanism is very compact and can be placed behind the Delta mechanism away from the working area (see Fig. 1).

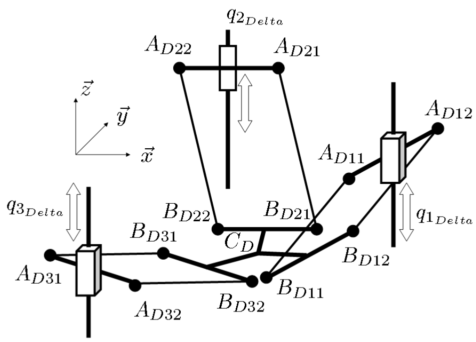
B. Modeling of the Delta mechanism

First of all, some hypothesis are made to have the simplest model as possible. The motor axis are placed at 120° to each other. The motors are linear. The only useful parameters of the delta mechanism are the difference between the radius of the base and the radius of the traveling plate $\Delta R = R_B - R_{TP}$ and the length of the arms L.
Figure 2 shows the geometrical parameters of the Delta mechanism. The coordinates of the traveling plate center C_D are x_{Delta}, y_{Delta}, z_{Delta} and the joint positions are $q_{1_{Delta}}$, $q_{2_{Delta}}$, $q_{3_{Delta}}$.
The Delta mechanism is optimized from the condition number of the jacobian matrix $\boldsymbol{J}_{Delta}$ which links operational speed $\dot{\boldsymbol{x}}$ to joints velocities $\dot{\boldsymbol{q}}$:

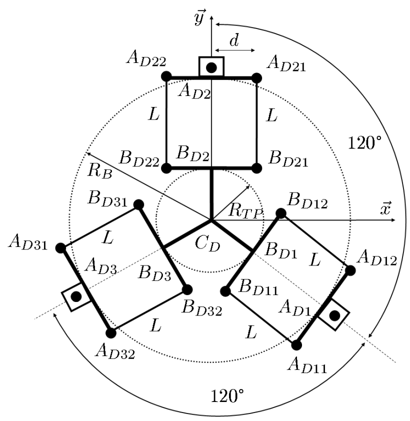
$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{Delta}\dot{\boldsymbol{q}} \tag{1}$$

The matrix $\boldsymbol{J}_{Delta}$ is given by:

$$\boldsymbol{J}_{Delta} = \boldsymbol{J}_x^{-1}\boldsymbol{J}_q \tag{2}$$



(a) 3D view



(b) Top view

Fig. 2. Delta geometrical parameters

where

$$\boldsymbol{J}_x = \begin{bmatrix} x_{Delta} - \frac{\Delta R}{2} & y_{Delta} + \frac{\Delta R\sqrt{3}}{2} & z_{Delta} - q_{1_{Delta}} \\ x_{Delta} & y_{Delta} - \Delta R & z_{Delta} - q_{2_{Delta}} \\ x_{Delta} + \frac{\Delta R}{2} & y_{Delta} + \frac{\Delta R\sqrt{3}}{2} & z_{Delta} - q_{3_{Delta}} \end{bmatrix} \tag{3}$$

$$\boldsymbol{J}_q = \begin{bmatrix} z_{Delta} - q_{1_{Delta}} & 0 & 0 \\ 0 & z_{Delta} - q_{2_{Delta}} & 0 \\ 0 & 0 & z_{Delta} - q_{3_{Delta}} \end{bmatrix} \tag{4}$$

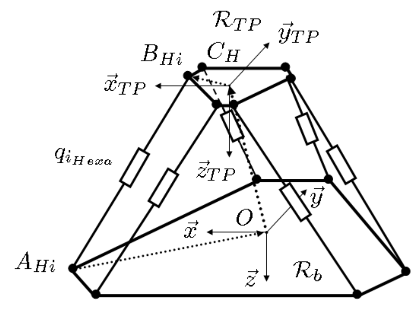
C. Modeling of the Gough platform

Figure 3 presents the parameters of the Gough platform. Points A_{Hi} which represents the centers of the spherical joints on the base are placed on a circle of radius r_b. Points B_{Hi} which represents the centers of the spherical joints on the traveling plate are placed on a circle of radius r_{TP}. Then, three lines passing by the base center O and the traveling plate center C_H and separated by an angle α_0 are defined. Points A_{Hi} (resp. B_{Hi}) are then located symmetrically to these lines, two by two, with an angle of α_b (resp. α_{TP}).
The joint position are noted $q_{i_{Hexa}}$ ($i \in [1, 6]$) and the coordinates of the traveling plate center C_H are x_{Hexa}, y_{Hexa}, z_{Hexa}.
For the optimization of the Gough platform, we need the jacobian matrix which can be calculated as follows:

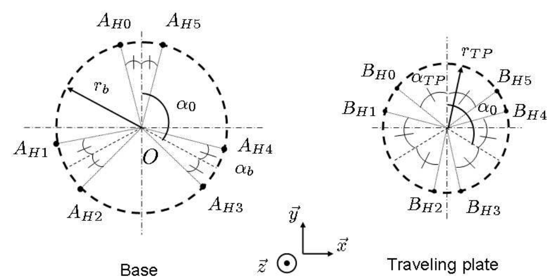
$$\boldsymbol{J}_{Hexa} = \begin{bmatrix} \boldsymbol{u}_1 & -\boldsymbol{u}_1 \wedge \boldsymbol{B}_{H1}\boldsymbol{C}_H \\ \vdots & \vdots \\ \boldsymbol{u}_6 & -\boldsymbol{u}_6 \wedge \boldsymbol{B}_{H6}\boldsymbol{C}_H \end{bmatrix}^{-1} \tag{5}$$

with

$$\boldsymbol{u}_i = \frac{\boldsymbol{A}_{Hi}\boldsymbol{B}_{Hi}}{q_{i_{Hexa}}} \tag{6}$$



(a) 3D view



(b) Top view

Fig. 3. Geometrical parameters of the Gough platform

III. OPTIMISATION OF THE ROBOTIC DEVICES

A. Presentation

The optimization consists in finding the best dimensions of the two robotic devices. The criterion of the optimization is very important and depends on the features we want to improve on the robots. The following paragraphs explain the chosen criteria.

B. Optimization of the Delta Mechanism

The condition number of the jacobian matrix described by (2) is used as the Delta mechanism optimization criterion. The goal of this optimization is just to insure that the Delta robot have an homogeneous behavior in the whole workspace in term of small displacements.
Figure 4 shows the maximum condition number of the jacobian matrix for a given workspace of $0.3 \times 0.3 \times 0.3$ m^3 according to the length of the arms L and the difference between the base radius R_B and the traveling plate radius R_{TP}. The dashed line represents the minimum of the worst condition number of the jacobian matrix. For a given length of the Delta mechanism arms L, ΔR can be calculated by the equation of this line:

$$L = 1.15\Delta R + 0.25 \tag{7}$$

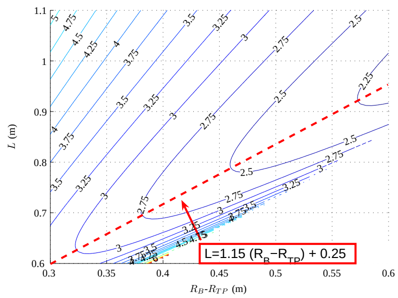


Fig. 4. Maximum of the condition number of the Jacobian matrix in a $0.3 \times 0.3 \times 0.3\ m^3$ workspace

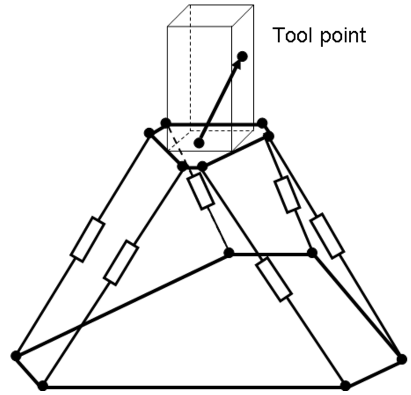


Fig. 5. Tool point and the bounding box

C. Optimization of the Gough platform

1) Introduction: The Gough platform needs to have a good repeatability, a good resolution and a good accuracy since it is the measuring system. This three positioning capabilities are not obtained in the same way.
To have a good repeatability, a particular care must be carried to the realization of the joints. Indeed, backlashes or friction in a joint is the main cause of a bad repeatability.
Concerning the robot accuracy, calibration is required to eliminated the positioning errors due to the difference between the nominal geometrical parameters and the real ones. Concerning the Gough platform, the calibration is very simple because the measuring legs can be calibrated with an artefact one by one and the position of the spherical joint centers on the traveling plate and the base can be measured with a coordinate measuring machine.
Finally, the last capability is the resolution of the robot. Resolution can be optimized during the design phase because it depends on the kinematical structure of the mechanism. We can optimize the dimensions of the robot links to improve the robot theoretical resolution. It is the subject of this part.

2) Optimization criterion: As was mentioned above the main purpose of the measuring Gough platform is to give information regarding the position of the tool only; this device has then to be optimized regarding its capability to give a good resolution for the tool position $\boldsymbol{Pos}_{Tool}$. Any small displacement of the Gough platform traveling plate, in position and orientation (respectively denoted $\boldsymbol{\delta Pos}_{Hexa}$ and $\boldsymbol{\delta Rot}_{Hexa}$) results in a small displacement for the considered tool point; this displacement is evaluated as follows:

$$\boldsymbol{\delta Pos}_{Tool} = \boldsymbol{\delta Pos}_{Hexa} + \boldsymbol{\delta Rot}_{Hexa} \otimes \begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} \tag{8}$$

where: $\begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix}$ is a vector which gives the position of the considered tool point with respect to the Gough platform traveling plate center (see Fig. 5).

The optimization process is then to minimize the norm of $\boldsymbol{\delta Pos}_{Tool}$, knowing the resolution of the measuring legs, in the 'worst case'; this 'worst case' has to be searched for all over the workspace and for a range of usable tools. Indeed a machine-tool or a robot is supposed to carry various tools whose length and diameter are not fixed. Thus L_x, L_y, L_z can vary within given ranges.

$\boldsymbol{\delta Pos}_{Hexa}$ and $\boldsymbol{\delta Rot}_{Hexa}$ can be expressed such as:

$$\boldsymbol{\delta Pos}_{hexa} = \begin{bmatrix} \sum_{i=1}^{6} J_{Hexa_{1i}} \delta q_{i_{Hexa}} \\ \sum_{i=1}^{6} J_{Hexa_{2i}} \delta q_{i_{Hexa}} \\ \sum_{i=1}^{6} J_{Hexa_{3i}} \delta q_{i_{Hexa}} \end{bmatrix} = \boldsymbol{J}_{Hexa_{Pos}} \boldsymbol{\delta Q} \tag{9}$$

$$\boldsymbol{\delta Rot}_{Hexa} = \begin{bmatrix} \sum_{i=1}^{6} J_{hexa_{4i}} \delta q_{i_{Hexa}} \\ \sum_{i=1}^{6} J_{Hexa_{5i}} \delta q_{i_{Hexa}} \\ \sum_{i=1}^{6} J_{Hexa_{6i}} \delta q_{i_{Hexa}} \end{bmatrix} = \boldsymbol{J}_{Hexa_{Ori}} \boldsymbol{\delta Q} \tag{10}$$

Equation (8) becomes:

$$\boldsymbol{\delta Pos}_{Tool} = \boldsymbol{J}_{Hexa_{Pos}} \boldsymbol{\delta Q} + \boldsymbol{J}_{Hexa_{Ori}} \boldsymbol{\delta Q} \otimes \begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} \tag{11}$$

$\boldsymbol{\delta Pos}_{Tool}$ can be considered as the position uncertainty due to the measurement uncertainty of the Gough platform legs $\boldsymbol{\delta Q}$. The goal of the optimization is to minimize this uncertainty.
First of all, an upper bound of this uncertainty has to be found considering the range of measurement uncertainty due to the resolution of the encoders of the legs of the Gough platform.

To simplify (11), the second term of its right member is rearranged as follows:

$$\begin{aligned} \boldsymbol{J}_{Hexa_{Ori}} \boldsymbol{\delta Q} \wedge \begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} &= - \begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} \wedge \boldsymbol{J}_{Hexa_{Ori}} \boldsymbol{\delta Q} \\ &= -\widehat{\boldsymbol{L}}_{xyz} \boldsymbol{J}_{Hexa_{Ori}} \boldsymbol{\delta Q} \end{aligned} \tag{12}$$

where

$$\widehat{\boldsymbol{L}}_{xyz} = \begin{bmatrix} 0 & -L_z & L_y \\ L_z & 0 & -L_x \\ -L_y & L_x & 0 \end{bmatrix}$$

Equation (11) can be rewritten:

$$\begin{aligned}\boldsymbol{\delta Pos}_{Tool} &= \boldsymbol{J}_{Hexa_{Pos}}\boldsymbol{\delta Q} - \widehat{\boldsymbol{L}}_{xyz}\boldsymbol{J}_{Hexa_{Ori}}\boldsymbol{\delta Q} \\ &= (\boldsymbol{J}_{Hexa_{Pos}} - \widehat{\boldsymbol{L}}_{xyz}\boldsymbol{J}_{Hexa_{Ori}})\boldsymbol{\delta Q}\end{aligned} \quad (13)$$

Finally a 6-dimension small displacement for the Gough platform is mapped into a 3-dimension displacement for the considered tool point by the following relation:

$$\boldsymbol{\delta Pos}_{Tool} = {}^{Tool}\boldsymbol{J}_{Hexa}\boldsymbol{\delta Q} \quad (14)$$

where: ${}^{Tool}\boldsymbol{J}_{Hexa} = \boldsymbol{J}_{Hexa_{Pos}} - \widehat{\boldsymbol{L}}_{xyz}\boldsymbol{J}_{Hexa_{Ori}}$
Looking for the 'worst case' requires to find the largest value of $\|\boldsymbol{\delta Pos}_{Tool}\|$ when each measuring leg encoder suffers from an uncertainty of ϵ:

$$-\epsilon < \delta q_i < \epsilon \quad (15)$$

This leads to consider on the one hand a 6-dimension polytop (in the space of the measuring legs) and on the other hand a 3-dimension polytope (in the Delta robot Cartesian space). To analyze the 6-dimension polytop, we resort to the tools described by Krut [20].
A vertex of the polytop of the hexapod legs small displacements are transformed by ${}^{Tool}\boldsymbol{J}_{Hexa}$ in a vertex of the polytop of the small displacements of the tool. According Krut, the maximum value of the tool small displacements is found on a vertex of the polytop. The upper bound of $\|\boldsymbol{\delta Pos}_{Tool}\|$ is the maximum of the distances between the origin of the polytop and its vertices.
Moreover, for a given $\delta\boldsymbol{Q}$, the fact that the tool point is considered in this paper inside a bounding box has to be taken into account.
Equation (11) can be developed as follows: δPos_{Tool} :

$$\boldsymbol{\delta Pos}_{Tool} = \begin{bmatrix} \sum_{i=1}^{6} J_{1i}\delta q_{i_{Hexa}} + \sum_{i=1}^{6} J_{5i}\delta q_{i_{Hexa}} L_z - \sum_{i=1}^{6} J_{6i}\delta q_{i_{Hexa}} L_y \\ \sum_{i=1}^{6} J_{2i}\delta q_{i_{Hexa}} + \sum_{i=1}^{6} J_{6i}\delta q_{i_{Hexa}} L_x - \sum_{i=1}^{6} J_{4i}\delta q_{i_{Hexa}} L_z \\ \sum_{i=1}^{6} J_{3i}\delta q_{i_{Hexa}} + \sum_{i=1}^{6} J_{4i}\delta q_{i_{Hexa}} L_y - \sum_{i=1}^{6} J_{5i}\delta q_{i_{Hexa}} L_x \end{bmatrix} \quad (16)$$

This leads to:

$$\begin{aligned}\|\boldsymbol{\delta Pos}_{Tool}\|^2 &= (S_1 + S_5 L_z - S_6 L_y)^2 \\ &+ (S_2 + S_6 L_x - S_4 L_z)^2 + (S_3 + S_4 L_y - S_5 L_x)^2\end{aligned} \quad (17)$$

with

$$S_j = \sum_{i=1}^{6} J_{ji}\delta q_{i_{Hexa}} \quad (18)$$

The squared norm is then studied as a function of L_x,L_y and L_z:

$$f(L_x, L_y, L_z) = \|\boldsymbol{\delta Pos}_{Tool}\|^2 \quad (19)$$

This function reaches a maximum when its gradient is null and when its hessian matrix is positive-definite. The system of equations which described that the gradient is null is:

$$\begin{cases} S_6(S_2 + S_6 L_x - S_4 L_z) - S_5(S_3 + S_4 L_y - S_5 L_x) = 0 \\ -S_6(S_1 + S_5 L_z - S_6 L_y) + S_4(S_3 + S_4 L_y - S_5 L_x) = 0 \\ S_5(S_1 + S_5 L_z - S_6 L_y) - S_4(S_2 + S_6 L_x - S_4 L_z) = 0 \end{cases} \quad (20)$$

The three equations of this system are not independent. Finally, the solution of this system is a line defined as follows:

$$\begin{cases} L_x \in \mathbb{R} \\ L_y = \frac{L_x(S_4^2 S_5 + S_5 S_6^2 + S_5^3) - S_5^2 S_3 - S_4^2 S_3 + S_4 S_6 S_1 + S_5 S_6 S_2}{S_4(S_4^2 + S_5^2 + S_6^2)} \\ L_z = \frac{L_x(S_4^2 S_6 + S_6 S_5^2 + S_6^3) + S_6^2 S_2 + S_4^2 S_2 - S_6 S_5 S_3 - S_4 S_1 S_5}{S_4(S_4^2 + S_5^2 + S_6^2)} \end{cases} \quad (21)$$

Then it is necessary to study the hessian matrix to qualify the critical points of the function (that is, determining if they are maximum or minimum):

$$H(f) = \begin{bmatrix} 2S5^2 + 2S6^2 & -2S5S4 & -2S6S4 \\ -2S5S4 & 2S4^2 + 2S6^2 & -2S6S5 \\ -2S6S4 & -2S6S5 & 2S4^2 + 2S5^2 \end{bmatrix} \quad (22)$$

This matrix is constant whatever L_x, L_y and L_z. The determinant of this matrix is null and its eigenvalues are $\sigma_1 = 0$ and $\sigma_2 = \sigma_3 = 2S_6^4 + 2S_5^2 + 2S_4^2$. So, the matrix $H(f)$ is positive semi-definite. Thus there is no maximum for $(Lx, Ly, Lz) \in \mathbb{R}^3$. So if there is a maximum it belongs to the boundary of tool bounding box.
Additional analysis is then required; firstly, each face of the bounding box is analyzed; for example, by setting L_x to its maximum value, a plane corresponding to one of the faces is defined, and the function in (19) becomes a new function with two variables only. This new function is treated as the first one, that is, analyzing its gradient and hessian matrix. It is determined that there is no maximum on those planes. The maximum are then to be found on edges.
Again, lines corresponding to the edges are defined by setting two variables of (19) to their minimum or maximum values. The same derivation is performed again and no maximum can be found on those lines. The conclusion is that the maximum is on the vertices.
Finally, to find the upper bound of the norm $\|\boldsymbol{\delta Pos}_{Tool}\|$ for a given point of the Delta workspace, it is necessary to calculate this norm for all the tool bounding box vertices (2^3 possibilities) and all the vertices of the Gough platform 6-dimension polytop (2^6 possibilities). Then, we take the maximum value among the 2^9 values calculated. The worst point throughout the workspace is established thanks to a numerical optimisation routine and finally, the Matlab function `fmincon` is then used to search the optimal design that will minimized this upper bound worst case.

3) Optimization constraints: There are two constraints, in addition to the workspace constraint, to respect during the optimization process. First of all, collisions between the legs of the Gough platform and the Delta arms have to be avoided. A collision check has been integrated in the optimization algorithm. Another constraint is the bounds on the measuring legs and has been taken into account as well.

IV. OPTIMIZATION RESULTS

A. Delta parameters

Equation (7) gives the relation between the length of the Delta arms L and the difference between the base radius and the traveling plate radius, ΔR. For practical considerations, the length of the Delta arms L is fixed to $0.8\ m$. So, the difference between the base radius and the traveling plate radius, ΔR is equalled to $0.48\ m$.

For the design of the final machine, it is necessary to select the values of the traveling plate radius R_{TP} and the length d which is the distance between the center of the spherical joints of the Delta robot parallelograms. The traveling plate must be large enough to support a spindle. It is chosen equal to $0.06\ m$. Concerning the length d, it is better to take the bigger possible value to avoid the parasitic movements of the traveling plate due to the dimension errors of the Delta arms. Finally, the value of the length d is $0.075\ m$.

B. Gough platform parameters

The Gough platform optimisation has to take into account the Delta geometry to avoid collisions. The distance between the center of the two structures is chosen such as it is the smallest possible to minimize the size and the weight of the traveling plate. This distance is equal to $0.1\ m$.

A preliminary study showed that the optimization criterion of the Gough platform is better if the angles α_b and α_{TP} are small and if the radius r_b and r_{TP} are big. Considering this and the collisions aspect a first set of parameters are chosen to initialize the optimization algorithm.

The final values of Delta parameters and Gough platform are presented in Table I and Figure 6 shows the final design of the machine-tool prototype which is in manufacturing phase.

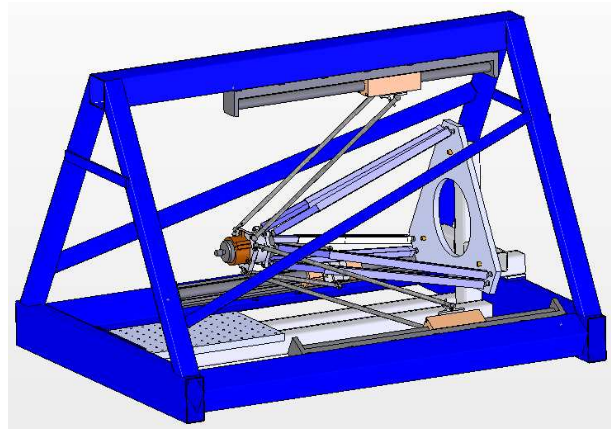
TABLE I

DELTA AND GOUGH PLATFORM PARAMETERS

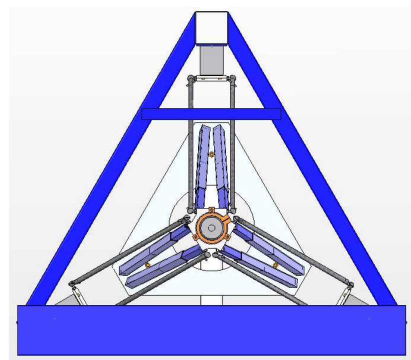
Delta parameters		Gough platform parameters	
R_B	540 mm	r_b	375 mm
R_{TP}	60 mm	r_{TP}	75 mm
L	800 mm	α_b	6 $^\circ$
d	75 mm	α_{TP}	20 $^\circ$
Other parameter			
$\|C_H C_D\|$	100 mm		

V. CONCLUSIONS

In this paper we have proposed the design and the optimization of a parallel machine-tool composed of an actuated parallel 3-dof mechanism (a linear Delta) and (ii) a measuring 6-dof mechanism (a Gough platform)). We have explained the interest for a machine-tool to have a measuring device independent of the actuated mechanism notably to measure the consequence of its deformations due to the machining efforts. Finally, we have proposed an optimization which is performed to obtain the best resolution for the measuring system evaluated at the tool level. The final design of the coming prototype is shown in Fig. 6. Different control strategies will be evaluated on the prototype for example online calibration, compensation or control of the machine in the measurement system space.



(a) 3D view



(b) Front view

Fig. 6. Final design of the machine-tool prototype

VI. ACKNOWLEDGMENTS

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