ORION MINANGLE: A FLEXURE-BASED, DOUBLE-TILTING PARALLEL KINEMATICS FOR ULTRA-HIGH PRECISION APPLICATIONS REQUIRING HIGH ANGLES OF ROTATION

Patric Pham, Yves-Julien Regamey, Maurice Fracheboud, Prof. Reymond Clavel

Laboratoire de Systèmes Robotiques (LSRO)
Ecole polytechnique fédérale de Lausanne (EPFL)
Station 9, 1015 Lausanne, Switzerland
patric.pham@epfl.ch

Keywords: Flexures, High Angles, Parallel Kinematics, Ultra High Precision, Double-Tilt, RCM

ABSTRACT

If you need to design ultra-high precision devices[1] for mechanisms with multiple axes there are not a lot of ways leading around flexure-based joints. Using this type of articulations totally eliminates backlash and friction and is, by this, providing an accurate mechanical foundation for your device. The most important disadvantage of this technology is the low range of motion. The basic joint types, blades and circular hinges, have angular limits which strongly depend on the targeted stiffness, the quantity of motion cycles and the elastic limit of the material. This article will introduce novel parallel kinematics which are totally based on 1 dof [2] flexures and whose angular range of motion is determined by twice the range of the single joint. It is a 3 dof parallel kinematics based on 3 identical kinematic chains which produces movements in θ_x, θ_y and Z. The model has been designed to constitute the left hand of a machine tool that requires to orient the workpiece in a very precise manner and with high rotation amplitudes. Additionally to this it presents very interesting characteristics of Remote-Center-of-Motion (RCM) mechanisms. This is a vital feature for applications where the linear movements are highly limited and should not be consumed by parasitic movements of other axes. All these features, combined with the advantages of parallel kinematics, makes the Orion MinAngle a very interesting concept.
The model has been designed with joints achieving $\pm 8^\circ$ leading to an output angle of $\pm 15^\circ$ on both rotation axes.

1. INTRODUCTION

In several domains like micro-machining or micro-assembly the tendency of miniaturization imposes to use more and more precise equipment to guarantee a satisfying and repeatable process. Additionally, since the complexity of workpieces and processes are increasing the same way, the need of higher angular strokes is present. Higher strokes stand for more liberty of action when designing workpieces or when planning a process.

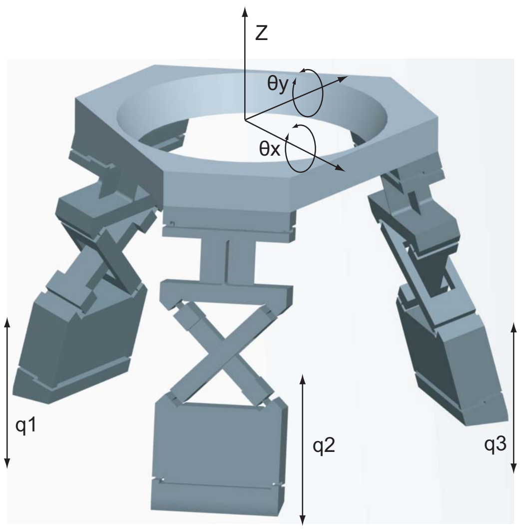

Figure 1: *Orion MinAngle in a simplified version*

Classical mechanisms using normal rolling or friction bearings are limited in their precision and repeatability because of friction, backlash and low joint stiffness. Applying flexible joint technology helps overcoming these problems but creates another one, which is the low angular stroke.
Henein [1] proposes an Orion kinematics based on flexures producing the same movements in θ_x, θ_y and Z. The system was designed for micro-assembly tasks and its rotation amplitudes achieve $\pm 3.5^\circ$. The ball-and-socket joints are made of flexible wires. This system is very interesting but presents only small motion range.
Pernette [2] proposed a special flexible pivot to obtain higher rotation amplitudes. His pivot consists of two simple joints in series, each of these absorbing half of the total angle. The movement of the central part, between the two

[1] Ultra-high precision assumes precisions and repeatabilities below the micron
[2] dof: degree of freedom

joints, has to be controlled by an additional mechanism. This work has resulted in a joint that performs really high angles but its complexity is restricting a real application. Hesselbach [3] proposes to change the joint material instead of designing special architectures. He is using pseudo-elastic discrete SMA components to achieve higher rotation amplitudes. Every simple joints can achieve $\pm 30^\circ$. Since the mechanics are not monolithic, it is hardly imaginable to use this concept for a ultra-high precision mechanisms.
The system proposed in this article is based on a novel kinematics which is familiar with the Orion proposed by Henein [1]. Unlike the normal Orion our system does not have explicit Ball-and-socket joints but is only constituted by simple pivots and a special architecture permits to have big rotation angles without using any special materials.

2. KINEMATICS

The Orion MinAngle is a parallel mechanism performing 2 rotations and 1 translation. It is constituted by 3 identical kinematic chains which are ideally[3] distributed every 120° around the robot output. Every chain is mounted on a linear guide which is oriented vertically (Z axis).
Figure 2 shows the isostatic kinematic scheme of the mechanism.

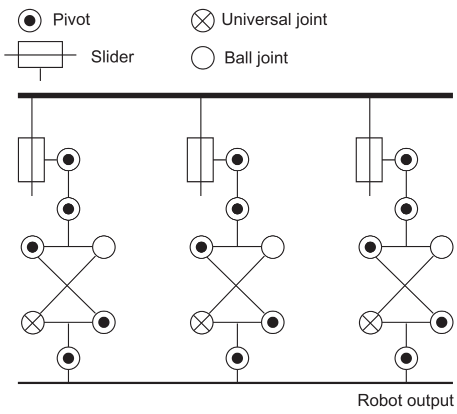

Figure 2: *Isostatic kinematic scheme of the Orion MinAngle*

For manufacturing and simplification reasons the universal and spherical joints have been replaced by simple pivots. Thanks to this replacement all the mobility of the output can be generated using only pivots whose dimensioning and fabrication is well known. Since all pivots are fabricated in the same step, all together in a monolith using Wire-EDM, the overcontrained system shouldn't induce problems of peak constraints.

[3]in terms of stiffness

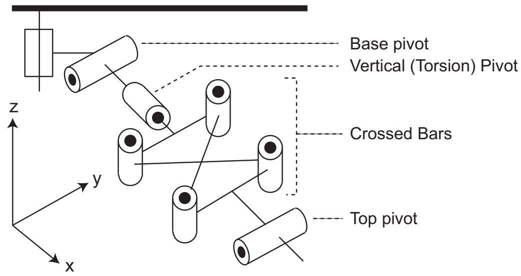

Figure 3: *Realization of the simplified, overconstrained kinematic chain using only pivots. The figure shows the orientation of the joints relatively to each other.*

3. MINIMIZING THE ANGLE AMPLITUDES

Each kinematic chain has to be able to perform 2 rotations in θ_x and θ_y with $\pm 15^\circ$ amplitude on each axis as well as a translation in Z which is not of importance in this chapter. To divide the output angle by 2 there need to be at least 2 pivots in series per axis. Now for both axes, θ_x and θ_y there is a different mechanism which guarantees that the angle will be divided on 2 equal parts.

1st rotation axis: The crossed bars system allows rotation around the axis which is perpendicular to the plane generated by the crossed bars. Given certain geometric relations (see section 4.1) the output angle is perfectly divided on the pivots of the crossed bars system.
Besides the rotation, the crossed bars system generates a lateral movement in the plane.

2nd rotation axis: To divide the angle on the second axis we are taking advantage of the lateral movement generated by the two other kinematic chains. It gives us enough parameters to optimize the movement and divide the angles on the Top and Base pivots (see section 4.2)

4. OPTIMIZATION

The main goal for the optimization is to achieve high stiffness without compromising the angular amplitude. As it is well known the stiffness of flexible hinges is in function of their amplitude, see [1]. By choosing good geometry parameters the structure perfectly distributes the angles between the hinges in a way that each hinge doesn't see more than half of the output angle.

4.1. Crossed bars

Angles variation in the crossed bars system: As seen on figure 4, the variation of the angles at the base level of the mechanism is (by symmetry):

$$variation = \upsilon_1 - \psi_1$$

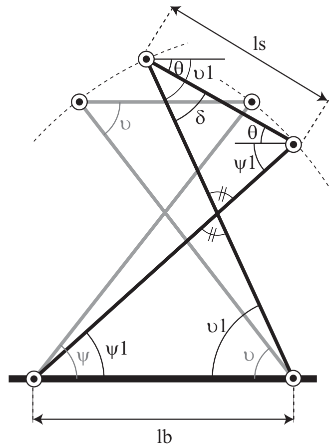

Figure 4: *Minimization of the Crossed Bars angle variation*

At top:

$$variation = (\psi_1 + \theta) - (\upsilon_1 - \theta) = \psi_1 - \upsilon_1 + 2\theta$$

By equalizing these two variations, we assure perfect angle distribution.

$$\upsilon_1 - \psi_1 = \psi_1 - \upsilon_1 + 2\theta \Rrightarrow \psi_1 = \upsilon_1 - \theta$$

Which implies:

$$\delta = \psi_1$$

This equality is true if and only if the two triangles formed by the crossed bars are similar. They are similar if and only if $l_b = l_s$.

In the next parts, for the sake of simplicity, the crossed bar system will be replaced by a simple revolute joint placed at the intersection of the bars see figure 5. This can be justified because the displacement of the rotation center creates a small displacement at the output, typically 1.5 % of the length of the bars ([1] page 99). It's negligible in front of the displacement due to the lever effect, around 13 % of the bar length.

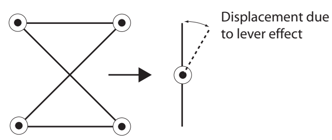

Figure 5: *Simplification of crossed bars system*

4.2. Base and Top pivots

The last thing to optimize is the angular variation of the two Base and Top pivots in series. This optimization has been conducted for a particular mouvement i.e. keeping two actuator fixed and moving the third one in order to rotate the output platform from $\theta = -15°$ to $15°$. With such a move only the two pivots in series (Top and Base) work in the moving arm (left arm in the figure), while in the two fixed arms (right arms in the figure) the crossed bars act like a single hinge, see figure 6. The angles of the two serial pivot in the moving arm are studied.

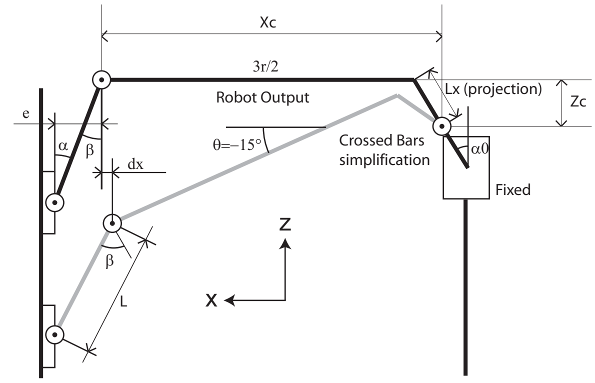

Figure 6: *Optimization of the Top and Base pivots. The plane defined by the crossed bars of the right arm is perpendicular to the plane defined by the crossed bars of the left arm. On the right side (fixed arms) only the crossed bars are moving, on the left side only the Base and Top pivots are moving.*

While the robot is rotating the end of the platform fixed to the mobile arm moves along a circle centered on the crossed bars of the fixed arms. This circle lies in the X-Z plane. The displacement of the end of the platform along the Z axis doesn't change the angles in the moving arm. The displacement dx along the X axis can be computed from:

$$dx = X_c(1 - \cos\theta) + Z_c \sin\theta$$

$$dx = (\frac{3r}{2} + Lx\cos 60° \sin\alpha_0)(1 - \cos\theta) + Lx\cos\alpha\sin\theta$$

Where α_0 is the value of α when $\theta = 0$, $Lx\cos 60°$ is the projection of Lx on the X-Z plane see figure 7. The first part of the equation is the X contribution (X_c) to dx while the second part is Z contribution (Z_c) to dx see figure 6.

Once dx is calculated we can derive α and β as:

$$\alpha = \arcsin\frac{e + dx}{L}$$

and:

$$\beta = \alpha - \theta$$

Then we calculate the amplitude (maximum in function of θ - minimum in function of θ) of α respectively β . Optimum is reached when amplitude of both angle is minimum i.e. when f is minimum.

$$f = \max((\max\alpha(\theta) - \min\alpha(\theta)), (\max\beta(\theta) - \min\beta(\theta)))$$

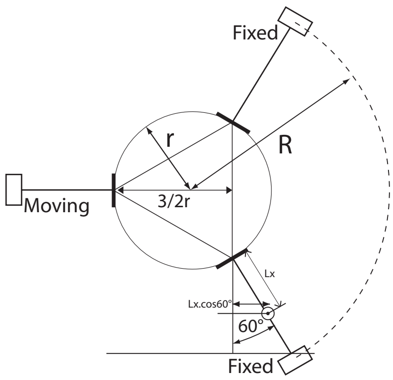

Figure 7: *Top view of the robot output*

The value of f depends of the geometric parameters: R, r, e, L, Lx. Where R is the outer radius of the machine see figure (general machine), r is the radius of the platform, L is the total length of an arm, Lx is the length from the center of the crossed bars to the end of the arm see figure 6, e is $R - r$; all these parameters are defined in figures 6 and 7.

A plot of f function of L and Lx, with $R = 117, e = 30, R = 87$, is shown on figure 8 . Chosen values for CAD design are $Lx = 70$ and $L = 140$.

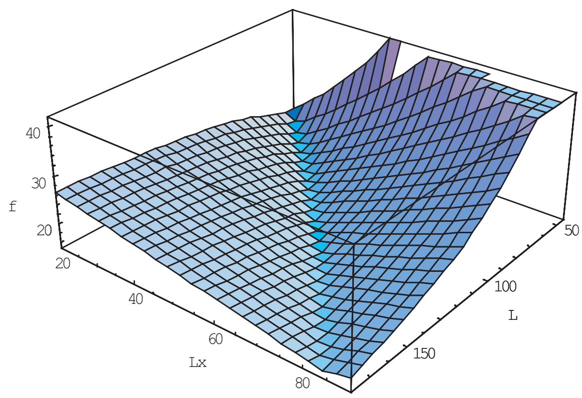

Figure 8: *f function of L and Lx. Optimal pairs of L and Lx can be found where f is minimal*

5. DIMENSIONING OF THE JOINTS

There are three things to consider when dimensioning a pivot using flexible technology: Angular range, fabrication constraints, stiffness in traction/compression modes and natural stiffness. All this quantities can be dimensioned using relatively simple formulas of structural mechanics. A good summary of those can be found in [1]. Dimensions are based on using K190 steel whose properties are summarized in the next table.

	young modulus E [Gpa]	σ_d [Mpa]
K-190 steel	196	800

Since all the pivots (except the vertical) have the same angular characteristics the dimensioning has to be done only once for all: The angular limit is given by (α in radians):

$$\alpha_M = \frac{2\sigma_{adm} l}{Eh}$$

Figure 9 shows the definition of the geometric parameters.

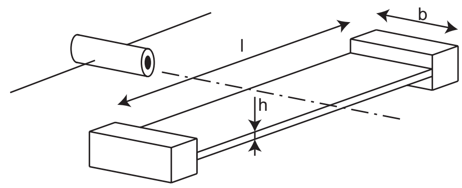

Figure 9: *Definition of the geometric parameters for a simple flexible blade. The pivot on the left stands for its kinematic representation.*

We desire an orientation device achieving $\pm 15°$, therefore we need a single blade achieving $\pm 7.5°$. This gives us a value for the ratio $\frac{l}{h} = 17$, present fabrication techniques allows an $\frac{l}{h}$ up to 60 (see [1]). Natural stiffness is

$$K_{\alpha M} = \frac{EI_y}{l}$$

with

$$I_y = \frac{bh^3}{12}$$

Choosing l and h big reduces natural stiffness but this also reduce transversal and torsional stiffness. Stiffness in traction is given by

$$K_{trac} = \frac{bhE}{l}$$

It directly depends of the angular limit through the ratio $\frac{l}{h}$. Chosen values for l and h are:

	length [mm]
l	3
h	0.160

For all pivots the parameter b was chosen as big as possible.

6. REALIZATION

The figure 10 shows a possible realization of the Orion MinAngle kinematics. The three monolithic kinematic chains have to be machined on a conventional milling machine to obtain the rough dimensions. The precise flexible blades are then machined using Wire-EDM (Electro Discharge Machining) to guarantee a nice surface finish and precise dimensions. The whole mechanism has been turned top-down and the robot output has been enlarged to place the TCP (Tool Center Point) into the RCM.

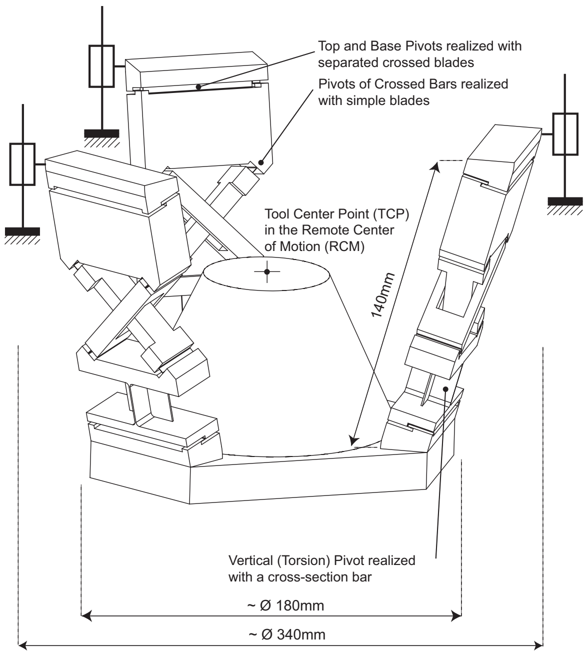

Figure 10: *Realization of the Orion MinAngle. The sliders can be realized with any type of technology, but ideally they should be designed using flexible linear guides.*

7. KINEMATIC MODEL

To verify the optimisation correctness we assembled a kinematic model with exactly the same geometric parameters. This model is represented in figure 11. The only difference between this kinematic model which is using perfect joint definitions and the monolithic flexure-based model is the small movement on the pivoting axes. In fact, when using blades as joints there is a small movement of the instantaneous rotation center. Given that this movement is really small (see [1]) and the purpose of the kinematic model is only validation of our optimization concept, we can neglect it without problems.

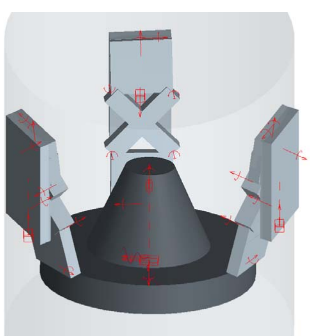

Figure 11: *Simplified kinematic model used for the measurement of the angles and parasitic movement.*

Figure 12 shows the nearly perfect division of the angles. The robot output was inclined by 15° and then rotated by 360° around a vertical axis. This movement will serve as a reference movement for the whole following kinematic analysis. It describes the limit of the motion range of the robot output. The z-axis is completely independent since all actuators move in this same direction. None of the angles performed more than $\pm 7.6°$

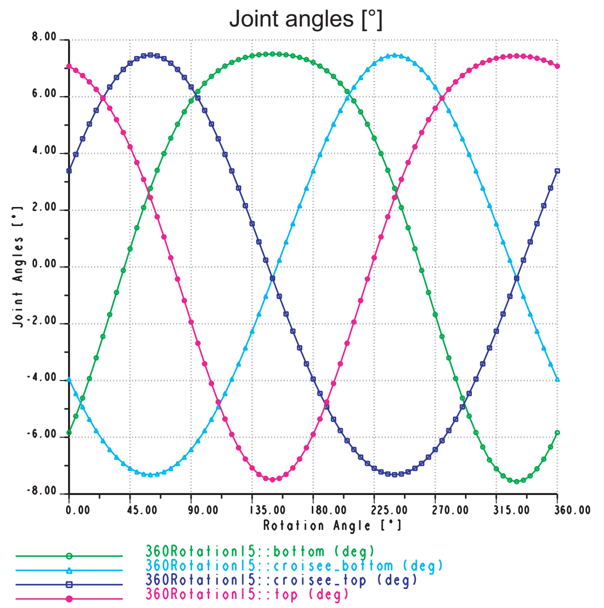

Figure 12: *Angles of all different pivots for a total 360°-cycle with 15° inclination*

The figure 13 shows the torsion angle for the same movement as before. The torsion angle is totally absorbed by the vertical pivot. It never exceeds more than $\pm 2.5°$. The vertical pivot is a crucial element of the whole kinematic chain. Although it does not execute a lot of angle it contributes a lot to the general stiffness of the whole robot and its movement generates a lot of additional contraints in the other flexures.

The figure 14 shows the parasitic translational movement of the Tool Center Point (TCP) for the same movement as before. The movement amplitude is quite small compared to the overall size of the robot. We almost have a perfect RCM movement.

8. FEM SIMULATIONS

In order to get an precise idea of the mechanical properties of the robot we analyzed its behavior using the FEM tool Pro/Mechanica™.

8.1. Maximal Internal Strain

The dimensioning of the articulations normally already takes the maximal internal strain into account (see section 5) to determine the maximum angular range. Since we have more than one joint and they all have a certain

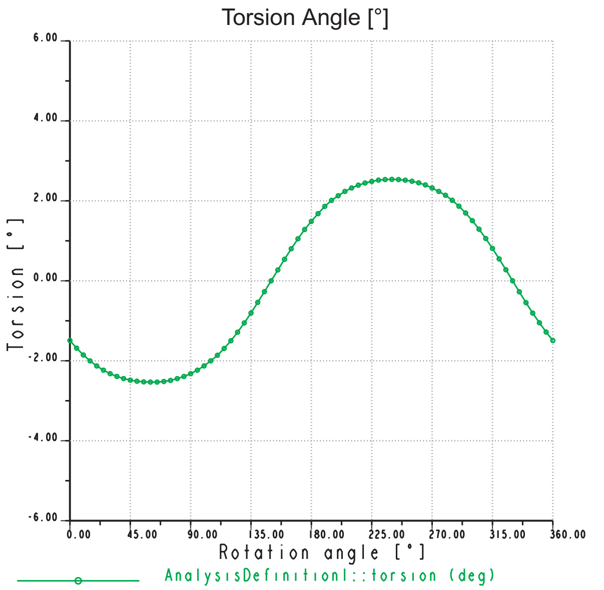

Figure 13: *Angle of torsion in the kinematic chain for a total 360°-cycle with 15° inclination.*

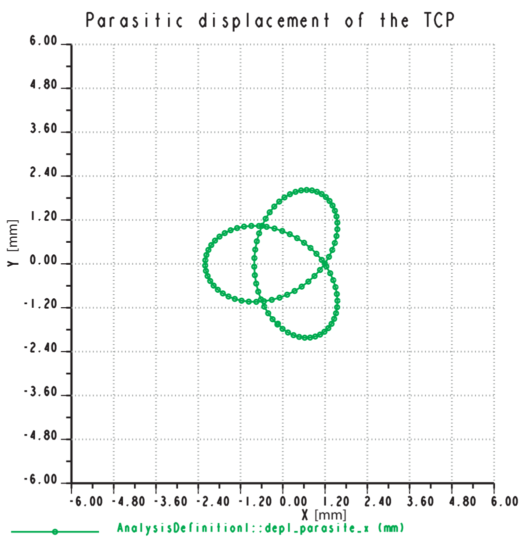

Figure 14: *Parasitic displacement in X-Y for a total 360°-cycle with 15° inclination. The movement in Z is lots smaller and could be compensated with the system's Z-axis.*

natural stiffness[4], there are some induced contraints that may exceed the limit of the single joint.
To verify this interaction we simulate the worst case which is, for one of the legs, at an rotation angle of 55° and 240° (of the whole cycle described before, see figure 13). At this moment the torsion is maximal and the weakest pivots, which are the pivots of the crossed bars, have their maximal deflection. The sum of both strains should not exceed $800MPa$ (see section 5). The FEM simulation at this very moment shows that the strain is very close to $800MPa$. The dimensioning of the vertical joint should probably be reinvestigated.

[4]The natural stiffness is the force/displacement ratio in direction of the degree of freedom of the joint

8.2. Stiffness

To calculate the stiffness of the system we considered its force/deformation behavior as linear for small deformations. A load of 1000 N was applied in a certain direction and the displacement was simulated and measured.

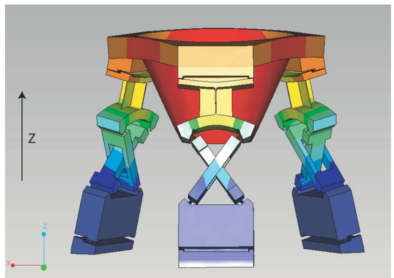

Figure 15: *The measured stiffness in z-direction amounts* ***70 N/µm***

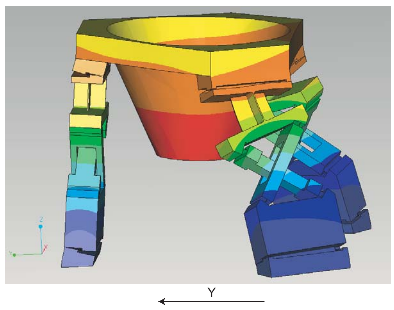

Figure 16: *The measured stiffness in y-direction amounts* ***4.2 N/µm***

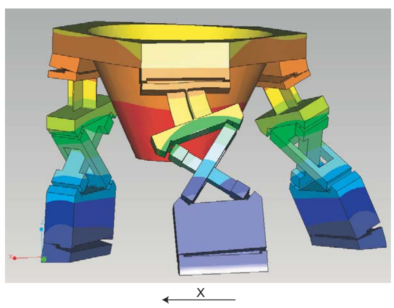

Figure 17: *The measured stiffness in x-direction amounts* ***4.2 N/µm***

8.3. Eigenfrequencies

A FEM-based modal analysis gave us an idea of the mechanical Eigenfrequencies:

Mode Nr.	Frequency [Hz]	Mode
1	186	Translation in Y
2	186	Translation in X
3	329	Torsion around Z

9. APPLICATIONS POSSIBILITIES

This chapter's ambition is to present an idea for a possible industrial application of the Orion MinAngle kinematics. The figure 18 shows the Orion MinAngle as left hand of a 5-axes parallel-kinematic machine tool. In this case the whole machine, both right and left hand, could be designed using only flexures, and by this constituting a complete ultra-high precision machine. The RCM capabilities would then be of high value because of the very restricted motion amplitude of flexure-based linear manipulators (in this case a DELTA). With both modules oriented like illustrated it is even imaginable that 2 axes share the same magnet rail of the linear motor or, depending on the guide technology, even the same linear guide. Linear motors are used to guarantee high stiffness, dynamics and high precision.

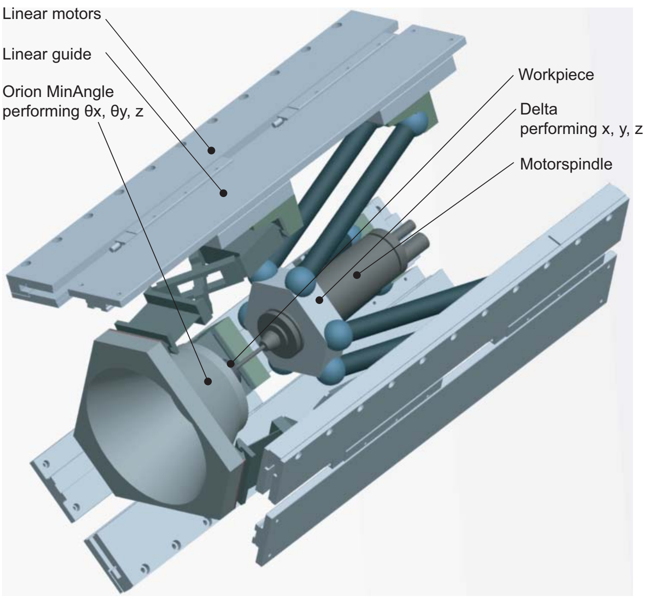

Figure 18: *Possible application of the Orion MinAngle as the left hand of a 5 axis high precision machine tool.*

10. CONCLUSIONS

The geometric properties of the kinematics proved to be very interesting for different types of applications. Its ability to double the range of a single joint, independent of the joint type and motion amplitude, makes it ideally suited for high angle applications.
The RCM capabilities are very precious for applications where the linear movement range is restricted and should not be used for the compensation of a parasitic displacement. Additionally, when high speeds are required, we can profit from the dynamics of the parallel kinematic since there is no other movement to compensate.
The next steps in developing this architecture will be:

- Optimization of the vertical pivot.
- Design and fabrication of a prototype. Choosing motors, linear guides and position sensors.
- Computation of the inverse and direct kinematics as well as the Jacobian matrix in order to allow the control of the prototype.

Even if the mechanical properties are convincing for the moment there is a very high potential of improvement if the vertical pivot is completely redesigned. In all the measures it proved to be the weak spot of the kinematics.
This article has presented a novel parallel kinematics for orienting movements with very interesting kinematic capabilities. It is very well suited to work with flexible joints since it is overcoming most of the problems of this technology, namely low motion range and complex spherical joints. In combination with a completely flexure-based right hand, which would be performing the translations, the Orion MinAngle presents a very high potential.

11. REFERENCES

[1] Henein, S., "Conception des structures articulées à guidages flexibles de haute précision", PhD Thesis N° 2194, EPFL Ecole polytechnique fédérale de Lausanne, 2000

[2] Pernette, E., "Robot de haute précision à 6 degrés-de-liberté pour l'assemblage des microsystèmes", PhD Thesis N° 1909, EPFL Ecole polytechnique fédérale de Lausanne, 1998

[3] Hesselbach, J., "Design and Analyses of a macro parallel robot with flexure hinges for micro assembly tasks", ISR 2004 International Symposium on Robotics, Paris, 2004

[4] Merlet, J.-P., "Parallel Robots", Kluwer Academic Publishers, 2000, ISBN 1-4020-0385-4