A new concept of modular kinematics to design ultra-high precision flexure-based robots

Murielle Richard, LSRO, Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland
Prof. Reymond Clavel, LSRO, Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland

Summary / Abstract

This work deals with the kinematic conception and the mechanical design of ultra-high precision robots, which are at present costly to develop, both in time and money. The aim of this paper is thus to introduce a **new modular concept of kinematics which allows to significantly reduce the time-to-market** and **a new double-stage flexure-based pivot.** Regarding the modular concept of kinematics, this ‘robotic Lego’ consists in a finite number of building bricks allowing to rapidly design a high precision machine and to easily modify its mobility. **The realised mock-up of a 4-DOF (Degrees of Freedom) robot, transformable into a 5-DOF one, validates this concept and the mechanical design of its bricks**. Flexure hinges are used to achieve the aimed sub-micrometer precision; however, existing flexure-based rotary joints are not able to fulfil the requirements of some applications, as they present a too low angular stroke and a parasitic motion of their centre of rotation. Thus, this paper also introduces **a new double-stage pivot based on blades working in torsion**; experiments performed on a prototype allow to **validate its principle and the simulation model** used for its development.

1 Introduction

The conception of robots capable of performing micro-manipulation and micro-assembly tasks with a sub-micrometer precision is becoming a crucial need as the current trend in numerous industrial domains is to miniaturise products, mainly microelectronic, optic and bio-medical devices [1]. The use of flexure-based mechanisms is compulsory to achieve this precision; **this paper thus introduces a new concept of modular kinematics to design ultra-high precision robots, as well as a new double-stage flexure-based pivot,** which compensates for the limitations of existing rotary articulations.

At the present time, the R&D process to design and build ultra-high precision machines is still highly costly, both in time and money. Therefore, methodologies of conception have been developed in order to reduce the time-to-market, for example in [2]. However, if the requirements of the robot are modified due for instance to a change in the industrial production line, the whole design process has to be restarted from the beginning, which consists in a non-negligible loss of resources. Therefore, the main aim of this paper is to introduce **a new modular concept of kinematics which allows to rapidly design a parallel robot and to modify only a small part of the whole kinematics to change its mobility**. This approach can be compared to a robotic Lego, where a finite number of conceptual bricks can be chosen, inverted and assembled within a small amount of time to create the desired machine. In parallel with the conceptual aspects, the design of the building bricks is elaborated in order to achieve the aimed sub-micrometer precision, therefore making use of flexure hinges [3]. This paper details the **realisation of a mock-up of a sub-micrometer precision 4-DOF (Degree of Freedom) robot, easily transformable into a 5-DOF one**. This allows to **validate simultaneously the modular concept and the mechanical realisation of the bricks** needed to build this kinematic solution.

Although many flexure-based joints have already been designed, for example in [3], these existing solutions are not always able to fulfil the requirements of the application; new high precision flexure-based articulations have thus to be developed in order to solve this issue. In particular, micromanipulation tasks cannot be effectively achieved using existing rotary joints, as they present too low angular strokes, as well as an upsetting parasitic displacement of their centre of rotation. Thus, this paper also presents **a new double-stage pivot based on blades working in torsion**, which has been elaborated to make up for these limitations. Experiments performed on a scaled-up prototype are used to **validate the principle of this articulation and the simulation model** used for its optimisation.

2 Concept of modular kinematics

2.1 Theoretical aspects

This new concept of modular kinematics consists in building a parallel robot composed of 1 to 3 kinematic chains, arranged orthogonally according to the faces of a cube. To do so, a finite number of conceptual bricks are used, namely the modules and the interfaces. The **modules** are active elements which motorise from 1 to 3 degrees of freedom, making use of linear actuators only. The rotational movements are thus performed by the differential motion of two linear motors of the same module; indeed, in order to preserve the modularity of the concept, the three kinematics chains are totally uncoupled, i.e. no differential motion is performed between them. Moreover, the position of the actuators is fixed, thus providing a standardisation of the connexions. As for the **interfaces**, they are passive elements whose function is to link the output of the modules to the robot end-effector, which is located on a corner of the cube. This configuration allows several robots to work together in a small volume. **Figure 1** illustrates the modular concept. At the present time, the combination of 7 modules and 13 interfaces allow to perform any robot mobility. As a result, a solution catalogue has been elaborated; **independently from any mechanical realisation, it lists between 1 and 9 solutions for each possible DOF arrangement**, therefore offering to the robot designer the opportunity to choose the most appropriate one according to the specifications.

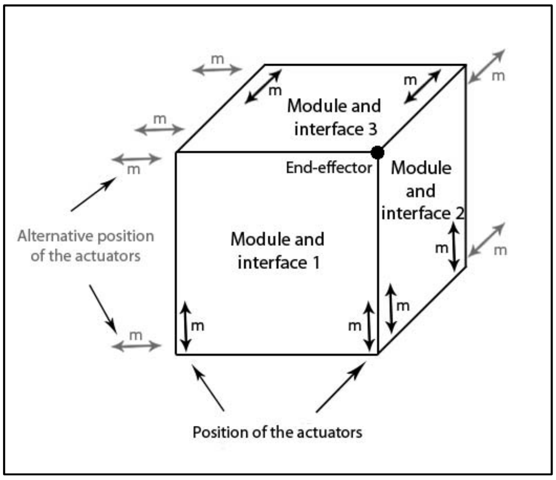


Figure 1 Concept of modular kinematics

2.2 Mechanical realisation of the bricks

As aforementioned, the kinematic solutions of the concept are independent from any technical realisation; the second step of the conception process therefore consists in developing the mechanical design of the modules and interfaces. As this step needs to be done only once for each building brick, the concept also provides a **mechanical solution catalogue**, in which the robot designer can choose the best technical realisation for the considered module or interface. As a consequence, the development process of modular robots is significantly shortened, which constitutes a crucial advantage over more traditional conception procedures. It is also to note that although this work focuses on ultra-high precision machines, the results of the concept can also be used to build machine-tools or any other type of industrial robots.

In order to obtain a sub-micrometer resolution, the use of flexure hinges is compulsory; this type of joints, machined by Wire-EDM (Wire Electro-Discharge Machining), indeed presents the advantages of being without wear and backlash [3]. The flexure-based mechanical design of some modules and interfaces is detailed in the following paragraphs.

2.2.1 T module

As its name indicates, this module performs a single translation motion. The most straightforward flexure-based design consists in a **4-hinge parallel table**, detailed in [3]. Note that the simple hinges can be substituted with cross pivots in order to compensate for the loss of rigidity occurring as the translational stroke increases. **Figure 2** shows the mechanical principle of this module along with a flexure-based cross pivot described in [3].

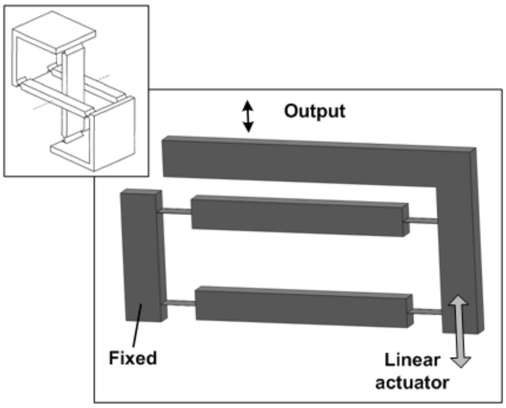


Figure 2 Principle of the T module and cross pivot developed in [3]

2.2.2 2T module

This brick is an extension of the previous one, as it performs two translations whose directions belong to the plane defined by the module. As the concept imposes that both actuators are oriented along the same direction, the solution consisting in using two aforementioned 4-hinge parallel tables is not adequate. Thus, the chosen mechanical realisation **makes use of a lever whose role is to change the direction of one linear motion**. This principle has been developed in [4] and is illustrated in **Figure 3**.

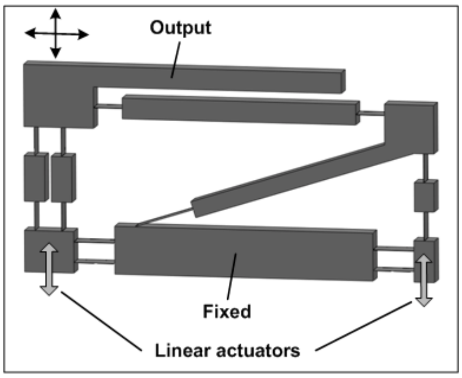


Figure 3 Principle of the 2T module

2.2.3 T-R module

This element performs a translation along an axis belonging to the plane defined by the module, as well as a rotation whose axis is orthogonal to this plane. The actuators also have to be oriented along the same direction; their synchronous motion performs the translation, whereas their differential action performs the rotation. Unlike the previously presented modules, a new mechanical realisation had to be developed to fulfil these requirements. The main originality of this design is **the possibility of choosing the position of the rotation centre**. It indeed makes use of a **RCM (Remote Centre of Motion)**, which deports the rotation centre at a point defined by the intersection of two flexure blades. The coincidence of the rotation centre with the end-effector of the robot aims at avoiding compensatory motions needed to keep constant the position of the output during the rotation. This point is crucial when the working volume of the robot is limited, which is the case with flexure hinges. **Figure 4** shows the principle of this module and a realised demonstration mock-up. Note that this brick can easily be transformed into a 'R module', which performs only the rotation around the orthogonal axis. Indeed, one actuator has to be removed and the corresponding mechanical part has to be linked to the fixed frame of the robot.

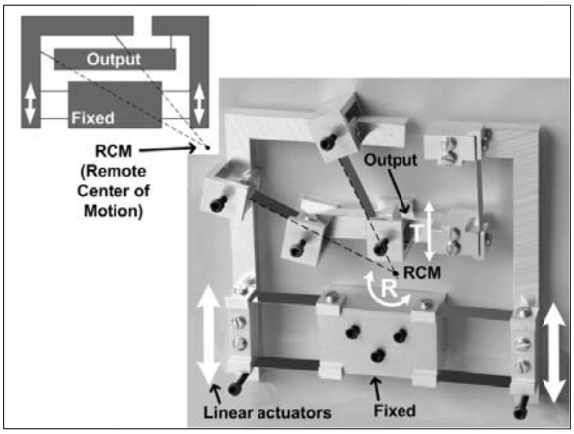


Figure 4 T-R module with a RCM: principle and mock-up

2.2.4 T-R-RT interface

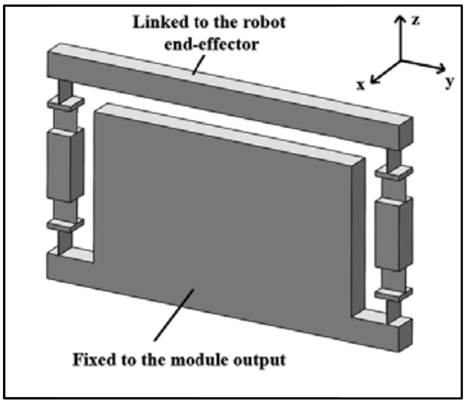


Figure 5 Mechanical principle of the T-R-RT interface

As aforementioned, the interfaces are passive elements whose function is to link the output of the modules to the robot end-effector. The realisation of two of these bricks is detailed here; the first one, the T-R-RT interface, performs 4 passive DOF, 2 translations and 2 rotations. As its name indicates, one translation is performed in the 1st direction, one rotation around the 2nd direction, and the two last degrees of freedom in the 3rd direction. For example, a possible orientation of this interface is Tx – Rz – Ry Ty. As for its mechanical design, it consists in two bars arranged in parallel, each of them being composed of 2 universal joints. **Figure 5** illustrates the principle of this interface.

2.2.5 3R-2T interface

Although the mechanical realisation of the previous interface presents a planar design, other arrangements are also possible. For instance, the 3R-2T interface, which performs 5 passive DOF (3 rotations and 2 translations), is efficiently realised in the form of an arm. This compact design thus only jams the translation along the axis of the arm. **Figure 6** shows a possible realisation, developed in [2]: 2 universal joints are serially arranged, along with a 4-blade torsion pivot, which allows a more controlled rotation motion than the only use of the torsion of the universal joints.

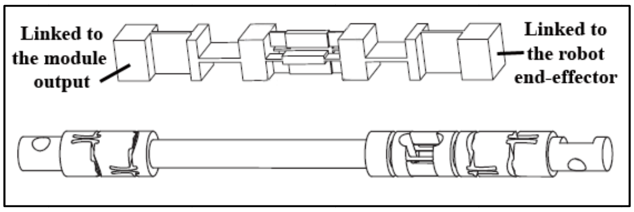


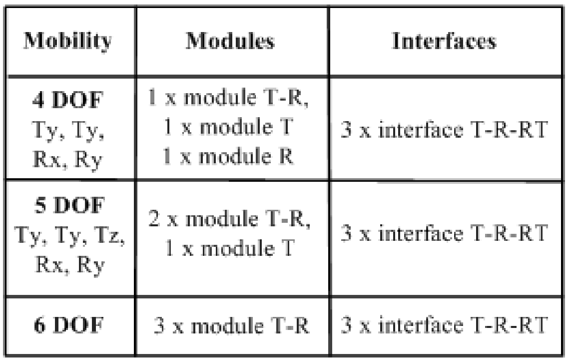
Figure 6 Principle (top) and Wire-EDM design (bottom) of the 3R-2T interface [2]

2.3 4-DOF to 5-DOF high precision robot

2.3.1 Choice of the kinematic solution

In order to validate the concept of modular kinematics and the mechanical realisation of the modules, the conception process is now applied to a concrete case. The considered DOF arrangement is a **4-DOF one, presenting 2 translations and 2 rotations around the same axes, for example Tx, Ty, Rx and Ry**. This mobility has been selected because it constitutes a typical example of motions requested for a micropositioning task: 2 translations in a plane, as well as tip and tilt orientations. This consideration directly leads to **the addition of the 5th degree of freedom, namely the vertical translation (Tz)**. This particular 5-DOF mobility, performing 3 translations and the tip and tilt rotations, is the most difficult kinematics to design, although it is also one of the most useful for industrial applications. The high precision robot which will now be designed with the modular concept will therefore present two versions: a 4 DOF one and, with as few modifications as possible, a 5 DOF one.

The solution catalogue of the modular concept proposes 8 and 7 possibilities for the 4-DOF, respectively 5-DOF cases; the most interesting one is selected and summed up in **Table 1**. This solution presents the **twin advantage of minimising the number of brick types needed to build it (3 different modules and 1 interface) and allowing to rapidly add the 5th DOF, by only modifying one module**: the R module has indeed to be transformed into a T-R one. As described in chapter 2.2.3, these two bricks are similarly designed; the addition of the 3rd translation is thus straightforward. Besides, the 6-DOF version of this robot is also trivial to achieve, making use of 3 T-R modules and 3 T-R-RT interfaces (see Table 1). **Figure 7** illustrates the kinematic principle of the 4-DOF version of this machine. Although not noticeable on Figure 7, the RCM principle described in chapter 2.2.3 is applied so that the centres of both active rotations are approximately coinciding with the robot end-effector.



Mobility	Modules	Interfaces
4 DOF Ty, Ty, Rx, Ry	1 x module T-R, 1 x module T 1 x module R	3 x interface T-R-RT
5 DOF Ty, Ty, Tz, Rx, Ry	2 x module T-R, 1 x module T	3 x interface T-R-RT
6 DOF	3 x module T-R	3 x interface T-R-RT

Table 1 Modules and interfaces needed to build the selected 4-DOF and 5-DOF solutions

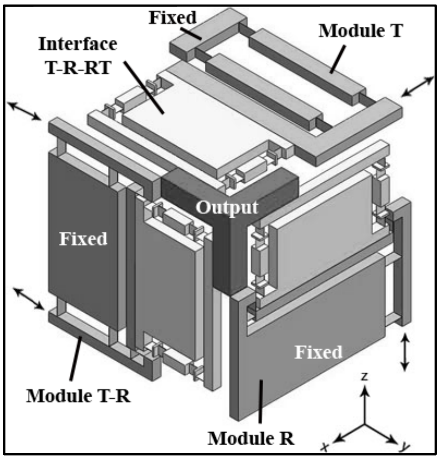


Figure 7 Kinematic principle of the 4-DOF version of the robot

2.3.2 Mock-up realisation

Now that the kinematic solution has been selected, the second step of the process is to choose in the mechanical solution catalogue the adequate design for the modules and interfaces. For the 4-DOF to 5-DOF robot, the required modules are T, T-R and R, whereas the sole required interface is T-R-RT; their realisation has been detailed in chapter 2.2. As aforementioned, all active rotations make use of the RCM principle, which allows their centres to be as close as possible to the robot end-effector. In order to validate the kinematic concept and the mechanical design of the bricks, a mock-up of this robot is realised. A building scale of 2:1 relative to the aimed robot size is chosen; as the parasitic motions of the realisations using flexure hinges are in the order of magnitude of the micrometer or less, the scaling effect allows to amplify these displacements, making them noticeable with the naked eye. Based on these observations, potential improvements could therefore be done before machining the Wire-EDM prototype. At this scale, the use of real flexure hinges is not possible; they are therefore replaced by assembled stainless steel blades, which is the most convenient way to simulate real Wire-EDM machined hinges. Finally, the characteristics of the mock-up are a total volume of 20 x 20 x 20 [cm^3], translational strokes of ± 10 [mm] and angular strokes of ± 10 [°]. As for the motors, they are simulated by manual activation. **Figure 8** shows the 5-DOF version of the realised mock-up.

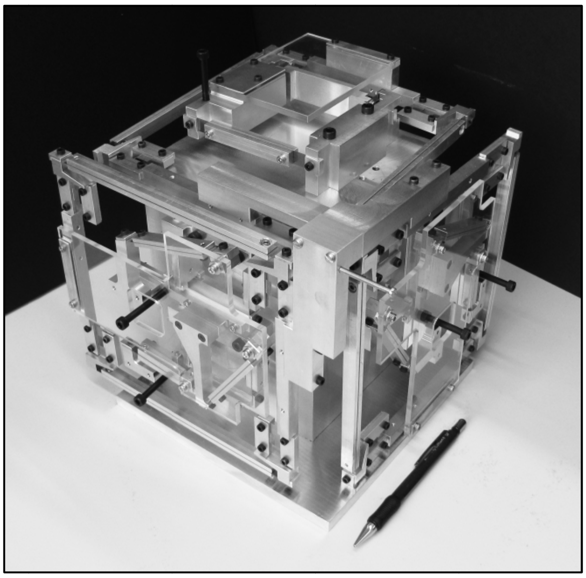


Figure 8 5-DOF version of the realised mock-up

The mock-up of this 4-DOF to 5-DOF robot allows to validate both the concept of modular kinematics and the mechanical realisation of the modules and interfaces. Indeed, its realisation proves that, with only 4 different building bricks, a 4-DOF robot can be designed within a very short time. Besides, its transformation into a 5-DOF one is straightforward thanks to the modularity of the kinematics.

3 Ultra-high precision double-stage pivot

3.1 Double-stage principle

Although many flexure-based joints have already been designed, for example in [3], the existing solutions are not always able to fulfil the requirements of the application. In particular, this is the case of rotary articulations, which present limited angular strokes as well as parasitic displacements of their centre of rotation. Some tasks which should be performed by high precision robots, for example micromanipulation, thus cannot be effectively achieved. The development of new solutions is therefore needed to solve this issue. This work focuses on the design of an original flexure-based 1-DOF rotary joint, i.e. a pivot.

Most existing flexure pivots are based on the flexion of Wire-EDM machined hinges or blades. Two examples of such realisations are particularly remarkable: a redundant rotary joint, developed in [3], and a ‘Butterfly pivot’ [5], present strokes of ±15[°] for parasitic motions of 1[µm] at 10[°]. Some rare designs take advantage of the torsion of flexure blades: a ‘treadwheel crane’ joint, described in [2], makes use of 4 blades in torsion (see also figure 6). However, the limitation of such a solution is the parasitic axial displacement of the mobile part during the rotation. Indeed, concentrations of constraints in the clamping of the blades create a parabolic deformation of the pivot output. A solution to this issue is proposed in [6], using parabolic blade clampings to achieve a constant deformation of the mobile part. However, this design is practically unrealisable by Wire-EDM.

The first originality of the articulation presented here thus consists in the optimisation of the shape of the blades in order to create a constant deformation of the whole mobile part of the pivot. Then, **the second novelty of the developed joint is the compensation of the parasitic axial displacement** by applying the principle proposed in [3] for a translation. It consists in serially arranging two pivots, (later named ‘stages’), presenting opposite parasitic motions; each of them is composed of 3 blades arranged at 120[°]. Then, a control mechanism imposes that the angular movement of the first pivot is exactly half the one of the second pivot. This design presents the twin advantage of totally compensating the axial parasitic displacement and multiplying by 2 the angular stroke, thus achieving more than ±20[°].

The first step of the development of this articulation thus consists in optimising the shape of the blades for the 1st stage of the pivot. Then, a 2nd stage, which is similarly designed, will be added, as well as the control mechanism which guarantees that the stroke of the 1st stage is half the one of the 2nd stage.

3.2 Optimisation of the flexure blades shape

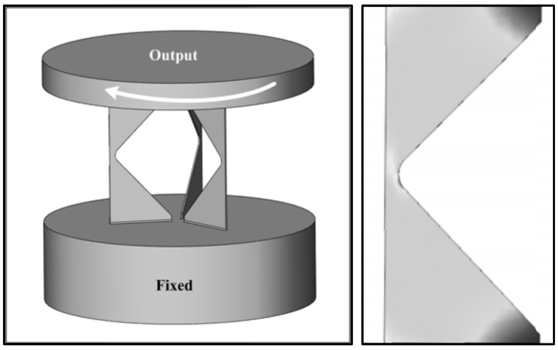


Figure 9 Left: optimised pivot / right: distribution of constraints (light gray = highest constraints)

The aim of this process is to find the optimal shape of the blades, i.e. the one which guarantees that the whole mobile part of the pivot stage performs the same axial displacement during the rotation. In other words, the optimisation has to minimise the deformation of the mobile part, which is achieved by decreasing the constraints in the clampings of the blades. The analytic formulation of the longitudinal normal stresses in the blades subjected to torsion is detailed in [7]; however, conducting a dimensional optimisation with such equations is not efficient; this procedure is thus performed in simulation, making use of SolidWorks 2008. As the blades are very thin compared to their length, the mesh has to be adapted in order to obtain significant results; a high quality, fine and alternative mesh is selected, with 36 elements in a circle. A pure torsion couple is applied to the mobile plate, while the following quantities are measured: angular displacement, mean axial displacement (evaluated on a diameter of the cylindrical output), difference between the maximal and minimal axial displacement of the output. The distribution of constraints resulting from the torsion also constitutes a point of interest.

As a result, the optimal design of the blades is a triangular shape, which is shown in **Figure 9, left**, whereas **Figure 9, right** illustrates the distribution of constraints in a blade when the torsion couple is applied.

3.2.1 Single-stage prototype

A prototype of the optimised single-stage pivot is realised in order to validate its concept and the simulation model previously used. Although this articulation is supposed to be made of steel, the aluminium alloy AlMgSi1 T6 is preferred for the prototype for economical aspects. However, as the ratio between the limit of elasticity and the Young modulus is smaller for aluminium, the angular stroke will also be reduced. Then, the prototype will be scaled-up relatively to its desired size; this creates an amplification of the parasitic displacements and allows their measurements with inductive probes. The dimensions of the blades are thus: 50 [mm], 25 [mm], 0.5 [mm] (length, breadth, thickness). The angular stroke is limited to ±4 [°] for this realisation, under an applied couple of 0.15 [Nm]; for this value, the simulation predicts a mean axial displacement of 41 [µm], as well as a difference between the maximal and minimal value of this displacement of 40 [nm]. **Figure 10** shows the Wire-EDM machined prototype.

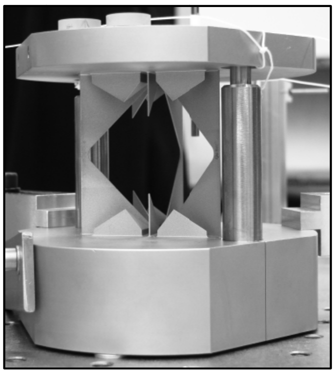


Figure 10 Wire-EDM machined aluminium prototype of the single-stage pivot

3.3 Experiments

The conducted experiments aim at validating the concept of the rotary articulation, as well as the simulation model used for its optimisation. To do so, the measurement setup is composed of two parts: an activation mechanism and a measurement system.

The aim of the **activation mechanism** is to apply a pure torsion couple to the mobile part of the pivot. To realise it, **a system of pulleys and calibrated weights is used**, which creates highly repeatable couples; both directions of rotation can be tested by changing the positions of the pulleys. As for the **measurement system**, its function is to evaluate the angular motion of the pivot, thus its torsion rigidity, as well as the axial displacement of the mobile part. Two Tesa GT22 inductive probes are used to measure the tangential motion of the pivot output, with a resolution of 1 [µm]. A simple trigonometric equation then returns the rotation angle with a resolution of 20 [µrad]. Concerning the parasitic motion, a vertically oriented Tesa GT22 inductive probe measures the axial displacement of the rotation centre with a resolution of 100 [nm]. **Figure 11** shows a picture of the experimental setup.

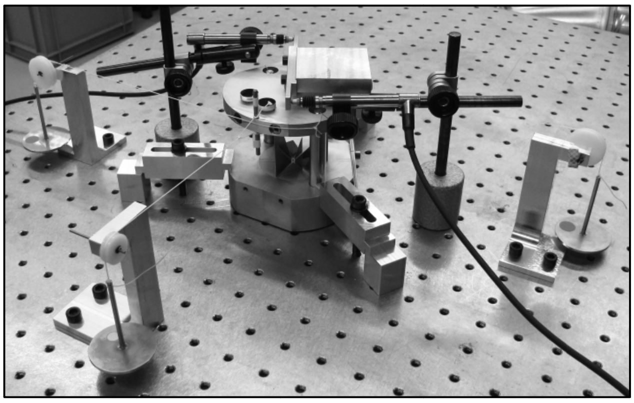


Figure 11 Experimental setup with pulleys and inductive probes

3.4 Results

3.4.1 Torsion rigidity

The measure of the natural rigidity of the articulation is obtained by applying a pure couple, whose value is comprised between 0 and 0.16 [Nm]. The tangential displacement of the cylindrical mobile part is evaluated with the probes; a simple trigonometric relation then returns the rotation angle, with a resolution of 20 [µrad]. **Figure 12** shows the obtained imposed couple / angle of rotation characteristic for one direction of rotation, as well as the simulated one; the slope of the line represents the compliance of the pivot, whereas the inverse of this quantity evaluates the torsion rigidity.

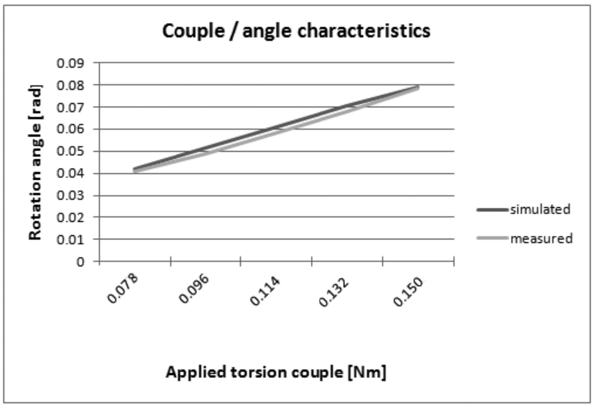


Figure 12 Measured and simulated compliance characteristic for one direction of rotation

The average of the measured rigidity is 2.01 [Nm/rad], whereas the mean simulation value is 1.93 [Nm/rad]; these two values are separated by an error of approximately 4 %. Moreover, as both the simulation and the measurements return a rigidity value which varies with the rotation of the pivot, **Figure 13** illustrates the evolution of this value with the applied torsion couple, evaluated with both procedures.

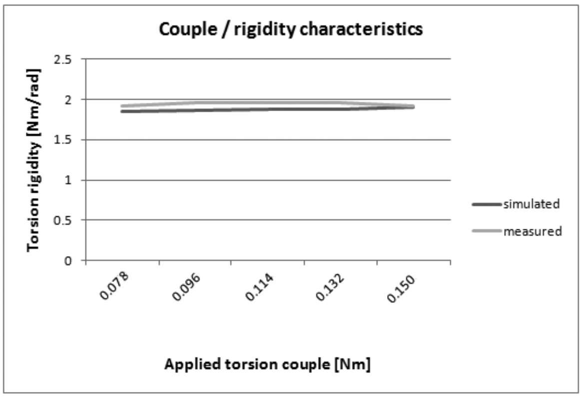


Figure 13 Measured and simulated rigidity in function of the torsion couple

The maximal error between the simulated and the measured characteristics is around 5 %. It is besides to note that the presented characteristics take into account the torsion couple created by the probes, as well as their rigidity.

3.4.2 Parasitic displacement

The axial parasitic displacement of the articulation during the rotation is evaluated at the centre of rotation; the vertically oriented probe performs this measurement with a resolution of 100 [nm]. As the design of the articulation is symmetrical, the parasitic displacement of the centre of rotation can be considered as a good estimation of the average value of this motion over the whole mobile part. The comparison of the value at the centre, measured with the probe, and the average displacement over the mobile part, evaluated with the simulation, is illustrated in **Figure 14.**

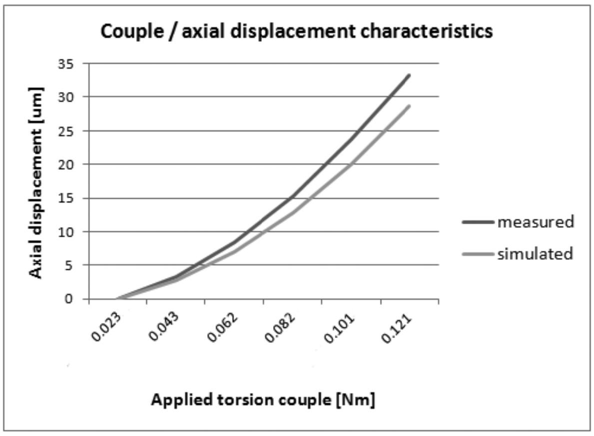


Figure 14 Measured and simulated axial displacement in function of the torsion couple

It can be noticed on figure 14 that the error between the mean simulated displacement value and the measured one grows with the torsion couple; besides, its maximal value is approximately 13 %. The direction of this axial displacement always tends to approach the mobile part of the pivot to its fixed part, independently from the direction of the rotary motion.

3.5 Discussion

The results of the torsion rigidity and rotation angle measurements under a varying couple match the simulated values, as they only present an error of 5 % compared to the simulation. As for the mean parasitic axial displacement of the pivot, the behaviour of this parameter is similar for the simulated and the measured values, presenting a paraboloic evolution with the rotary motion. The error of 13.5 % between these values is relatively high, but can be easily explained: the simulation model assumes a perfectly symmetrical pivot, which is in reality not the case because of the machining tolerances; these indeed cause a non-symmetrical behaviour of the articulation during the rotation motion. Thus, the average value of the mobile part deformation does not exactly match the value of this parameter measured at the rotation centre, which explains the obtained error.

This observation directly leads to the need of a more dedicated setup in order to locally measure the deformation of the pivot mobile part. However, the difference between the maximal and minimal values have been estimated to be 40 [nm] by the simulation; as this resolution is not achievable with the probes used for the setup detailed in this paper, strategies using other measurement principles are currently under study. The first one consists in using an **interferometer combined with an autocollimator** for local measurements of the pivot output; the first returns the linear axial displacement, whereas the second evaluates the parasitic inclination of the mobile part. However, this method requires the use of mirrors, which have to be glued on the top of the pivot. Even by making use of 3 spheres in order to obtain an isostatic and precise gluing, it is highly probable that the measurements will evaluate the orientation defects of the mirrors rather than the desired parameter. Thus, a second strategy consists in applying the principle of the **Moiré interferometry**: a pattern of lines is projected on the upper side of the pivot output; making use of a CCD camera, the analysis of the resulting pattern, which is deformed by the axial displacement caused by the rotation motion, returns the desired value along the whole mobile part. Although this technique is frequently used to control machined optical components, its application on aluminium parts leads to an estimated achievable resolution of 1 [µm], which is not sufficient here. The third strategy, which is now under study, is the use of the **Fizeau interferometry**, which is based on the difference of optical paths caused by irregularities on the measured surface. The achievable resolution would thus be sufficient; however, the upper side of the pivot output should be chemically polished in order to avoid that the measurements evaluate the roughness of the surface rather than the desired parameter. Besides, the future setup will also feature classical interferometers in order to evaluate the transverse and compression rigidities of the pivot.

To conclude, the results presented in this paper validate the simulation model for the rotation angle and torsion rigidity of the pivot; as for the axial parasitic displacement, the behaviour predicted by the model is conform to the measurements, whereas the absolute value of this movement is underestimated because of the assumed perfectly machined articulation. These observations allow to make the reasonable hypothesis that the behaviour of the deformation of the whole pivot output is correctly predicted. As for the absolute value, the simulation estimation is valid for a perfect pivot; for the real articulation, it is reasonable to consider that the measured value will be of higher magnitude. Besides, the value computed by the simulation is of the same order of magnitude as the digital computation precision. These two points confirm the need of a second measurement setup, which will allow to validate once and for all the simulation model concerning this parameter, as well as to evaluate the influence of the machining errors on the behaviour of the articulation.

4 Conclusion

First, this paper has presented a **concept of modular kinematics** which allows to build any possible robot mobility with only a finite number of active and passive elements. A conceptual solution catalogue has been elaborated, which proposes at least one possibility for any DOF arrangement. The mechanical conception of the building bricks, based on flexure hinges, has also been established, constituting a solution catalogue of possible designs. A **scaled mock-up of a 4-DOF robot, transformable into a 5-DOF one**, has been realised; the conception procedure as well as the design of the bricks has been detailed. The **viability of the proposed concept has thus been proved**, as well as its **capability of significantly shortening the time-to-market** of high precision robots. In addition, it has been shown that the concept offers a **convenient way of rapidly modifying the mobility of the robot** during or after the development process; it thus avoids restarting a whole procedure from scratch if the industrial needs were to change.

The next step now consists in **realising the real 4-DOF to 5-DOF robot by Wire-EDM**; this will allow to **characterise its dynamical performances** and will thus prove that they are at least similar to the ones of robots which are conceived with more traditional methods. Then, in order to achieve an absolute precision of around 10 [nm], the **calibration of the machine will be performed**, making use of the thermal and forces compensation procedure developed in [8].

Then, this paper has also introduced a **new double-stage flexure-based pivot**, which has been developed in order to achieve a high angular stroke, as well as to avoid parasitic displacement of the centre of rotation. A **scaled-up Wire-EDM machined prototype** has been realised in aluminium, allowing to perform measurements of these two parameters; **the results have validated the concept of this new pivot, as well as the simulation model used for its optimisation**.

The future work on this flexure-based articulation consists in **optimising the double-stage version,** in order to totally compensate the axial displacement of the 1st stage output. Then, the **control mechanism which guarantees that the stroke of the 1st stage is half the one of the 2nd stage will be designed**. Lastly, a **steel Wire-EDM real size pivot will be realised**; its characterisation will allow to prove the principle of compensation of the parasitic motion. This articulation will then be integrated in the design of the interfaces of the concept of modular kinematics.

5 Literature

[1] Tolfree, David: Commercialising Nanotechnology, concepts – products - markets, International Journal of Nanomanufacturing, vol. 1, n°1, 2006, pp. 117-133

[2] Helmer, Patrick: Conception systématique de structures cinématiques orthogonales pour la microrobotique, Ph.D. thesis n° 3365, Swiss Federal Institute of Technology Lausanne (EPFL), 2006

[3] Henein, Simon: Conception des guidages flexibles, Presses Polytechniques et Universitaires Romandes, Collection Meta, Lausanne, 2001

[4] Hodac, A.: A macro/micro-manipulator for high speed and accurate pick and place operations, Diss. ETH n°. 13148, Swiss Federal Institute of Technology Zürich (ETHZ), 1999

[5] Henein, S. et al.: Flexure Pivot for Aerospace Mechanisms, in. Proc. of 10th European Space Mechanisms and Tribology Symposium, Spain, September 2003

[6] Hale, L. C.: Principles and Techniques for Designing Precision Machines, Ph.D. Thesis, Dept. Of Mechanical Engineering, Massachussetts Institute of Technology, 1999

[7] Timoshenko, S: Strength of Materials, Part II: Advanced Theory and Problems, Second Edition, D. Van Nostrand Company, Inc, New York, 1947

[8] Lubrano, E. et al.: Modeling and compensation of cutting-forces generated during the EDM process for ultra high-precision robots, to be published at ISR Robotik 2010, Münich