Proc. of International Advanced Robotics Programme; Wokshop on Micro Robots, Micro Machines and Systems. Moscow, Russia, 24-25 November 1999.

Articulated structures with flexible joints dedicated to high precision robotics

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Abstract

This paper starts by presenting several examples of original flexible bearings and flexible articulated structures having 1 to 6 degrees of freedom to illustrate how flexures can soundly be used in high precision robotics. Then, the influence of the electrodischarge machining process on the joints' surfaces is discussed. Finally, an original setup for the fatigue testing of small flexures is briefly described.

1. Introduction

In the fields of semiconductors, opto-electronic interconnections and micro-systems in general, the demand for precise positioning has grown along with the increasing miniaturization of the structures which are to be handled or tested. The automatic manufacturing and assembly of these devices, which allows mass production at very low costs, require micromanipulators with ever higher precision.

In many cases an inappropriate mechanical structure for a manipulator can be an insurmountable limiting factor to its precision. For example backlash, friction or low stiffness can hardly be overcome by sensors or controllers. An efficient approach to this problem is to use a new concept of structures specially dedicated to high precision micro-manipulators. It consists in replacing the traditional rolling or plain bearings by flexible bearings.

This paper presents this approach through several examples ranging from simple one degree-of-freedom (DOF) flexible bearings to complex structures having up to 6 DOF. Some experimental results related to the manufacturing technology are also briefly described.

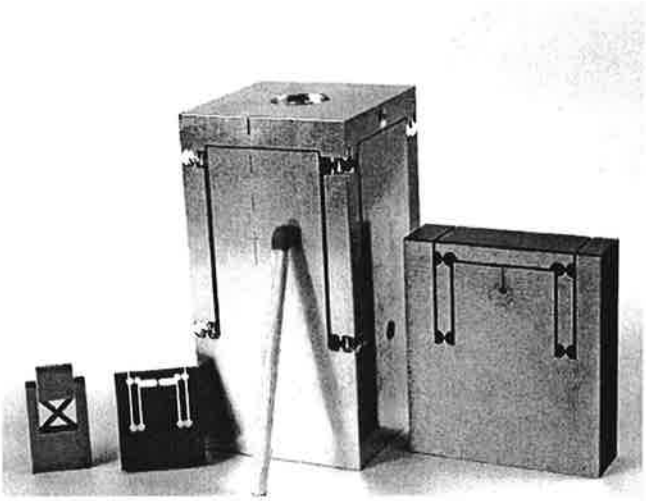

Fig. 1. Examples of monolithic flexures. From left to right : cross spring pivot (tempered steel); linear stage with 4 necked down flexures 25μm in thickness and a motion range of 0.5mm (tempered steel), X Y θZ stage (Perunal Aluminum alloy), linear stage. The match stick is 50mm long.

2. Advantages of flexures

Like plain or rolling bearings, flexures are joints connecting solid members and permitting relative motion in some directions while constraining motion in others. But whereas the two former types of bearings rely upon the friction or rolling of solid bodies on each other, flexures use the elastic properties of matter. This brings numerous advantages for high precision mechanisms:

- Absence of solid friction : plain or rolling contact between solids inevitably generates friction which alters the joint's functioning. Friction dissipates energy, provoking mechanical hysteresis. At low speed it causes halting motion due to the "stick & slip" phenomenon which limits the resolution of the movements. Finally friction is at the origin of wear. Flexure are free from all solid friction. Solely remains the internal friction of matter which is practically negligible.

- Absence of wear : wear reduces the precision of plain and rolling bearings because it alters their geometry and increases their mechanical play. Moreover, it is the principal factor limiting their life-time. Flexures do not suffer from these drawbacks and have their life-time limited only by the eventual fatigue of the material. Good design maintaining the stresses below the fatigue limit allow to guarantee almost infinite life-time.
- Absence of mechanical play : to reach high precision, plain and rolling bearings often require complicated play compensation. By definition, flexures have no play.
- High rigidities : the more rigid the mechanical structures of machines, the more precise they are statically (when external loads are applied) and dynamically (when vibrations occur). The rigidity of rolling bearings depends on the pressure of rolling elements on top of a rolling surface. With small bearings, the small radiuses of the rolling elements limit rigidity. Well designed flexures can be much more rigid than rolling bearings.
- Compact and monolithic structures : plain and rolling bearings are made of many mechanical parts which are assembled. This assembly increases their bulkiness and reduces their construction precision. Wire-electrodischarge machining allows to manufacture very complex flexible structures monolithically, thus providing high compactness and precision.
- Immunity to contamination : the wear and required lubrication of plain and rolling bearings frees particles of matter which can pollute the air of clean rooms. On the contrary, when used in dirty environments, dust can easily hinder or even block these bearings. Flexures are perfectly clean and are not affected by dirt.

3. Wire Electrodischarge Machining

As it has been clearly noticed, the main limitation of flexures is their short range of motion. It is due to the stresses in the flexures which must be kept below the yield stress of the material. The need for long strokes calls for flexures of ever thinner cross-sections. Wire electro-discharge machining (wire EDM) has shown to be one of the most suited manufacturing processes for this purpose, for it allows the manufacturing of necked down sections of various shapes with thicknesses thinner than 50μm, geometrical tolerances of the order of ±1microns and low surface roughnesses. Moreover, the machined pieces are not subject to any mechanical stresses which could alter their geometry, and materials with very high elastic limits can easily be machined.

4. Examples of flexures

The simplest and most common of all flexures are probably the parallel spring stage (fig. 2) and the cross spring pivot. They are usually made of discrete parts which are assembled. The advent of new manufacturing techniques like laser cutting and especially wire-EDM made possible the realization of monolithic structures with much more complex shapes and better guiding properties. The parallel spring stage of figure 1, for example, has a higher loading capacity and a higher stiffness ratio than the parallel leaf spring stage (fig. 2). Moreover, it does not suffer from the inaccuracies due to assembly tolerances, and can be miniaturized much more (see for example the small RCC pivot on fig. 3).

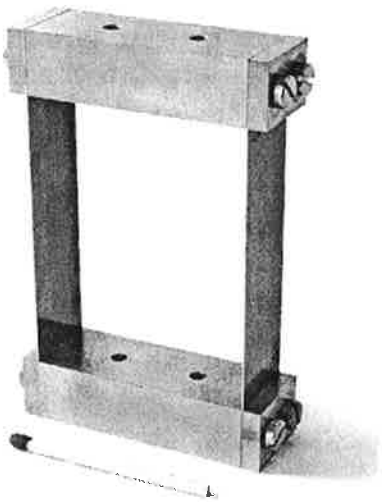

Fig. 2. Parallel leaf spring stage.

This same approach can be pushed further to realize more complex bearings. Figure 1 shows, among other flexures, a three DOF monolithic flexure and figure 4 shows a two DOF stage. These two examples illustrate the fact that flexible structures call for special kinematics which are different from the ones used with analogous plain or rolling bearings. In flexures, the moving part is often connected to the fixed base via several kinematic chains which constitute parallel structures.

Figure 5 shows another monolithic XY flexible stage which is composed of two parallel spring stages placed in series at 90° with respect to each other. This flexure has been actuated using voice coil actuators (Fig. 6). Figure 7 shows a parallel spring stage with four circular flexible hinges which is driven by two reluctant electromechanical actuators. The use of electromechanical actuators to drive flexures presents the great advantage of not introducing any friction in the system, thus allowing extremely high precision. But flexible structures can also be driven by traditional screw-nut systems and DC motors and still achieve good resolutions. The Orion three DOF robot shown in figure 8 has a resolution of 0.8μm although it is driven by simple power-screws.

As explained before, the main limitation of flexures is their short range of motion. To overcome this drawback two identical flexures are frequently placed in series to double the motion range. A very common example of this type of arrangements is the compound parallel spring stage [1]. Figure 9 shows an original design of a compound cross spring pivot. It is constituted of two RCC pivots (similar to the one of fig. 3) which are placed in series to double the motion range. It is essential to notice that placing two identical joints in series inevitably results in an idle internal DOF in the structure's kinematics. If external forces can excite this idle DOF, then the corresponding links of the structure will move. These parasitical internal movements can reduce greatly the overall stiffness of the structures. To solve this problem, enslaving mechanisms can be used. The slave compound rectilinear parallel spring stage [2] is a common example of such a solution. The pivot of figure 9 has an original rotative enslaving mechanism which suppresses the idle DOF of the structure, greatly increasing the radial stiffness of the pivot. Experimental measurements run on this piece showed that the slaving mechanism increases the radial stiffness of this long stoke pivot by a factor 10.

The pivot of figure 9 has been used to articulate the structure of a six DOF parallel robot called Tribias (fig. 10) [3]. This robot has three identical legs. Each of them is constituted of a plain ball joint and a flexible pivot joint. The latter is composed of a pair of identical long stroke pivots.

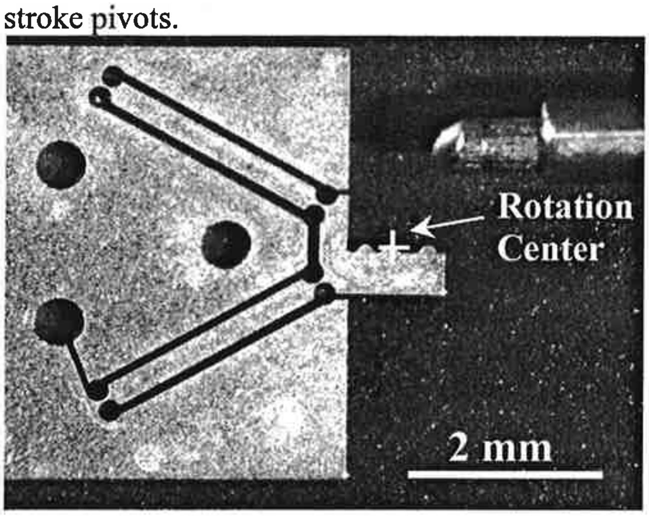

Fig. 3. Monolithic Remote Center Compliance pivot. The circular flexure hinges are 19μm in thickness. The tip of the pen on the upper right hand side is 0.7mm in diameter.

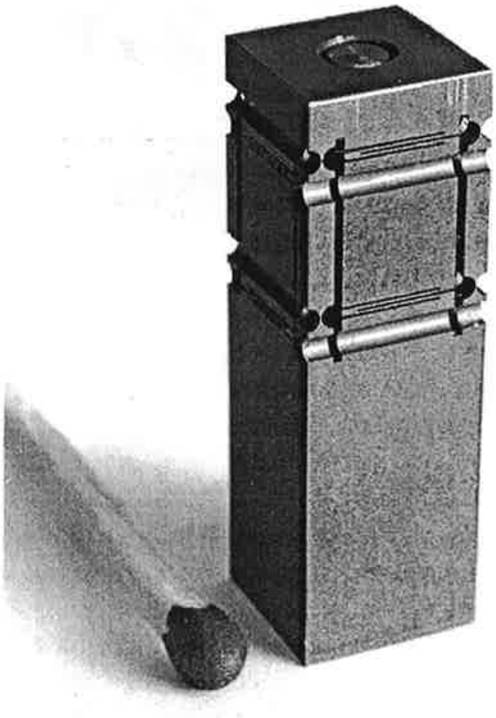

Fig. 4. Monolithic XY stage with integrated flexible bellow (tempered steel). The flexible parts are 25μm in thickness, the motion range is 0.5mm. The part is 30mm in height.

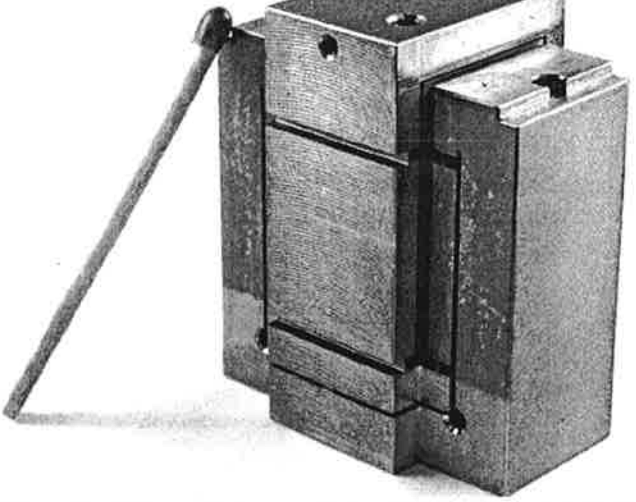

Fig. 5. Monolithic serial XY stage. Motion range: ±1mm; thickness of flexible parts: 60μm; material: titanium alloy TiAl6V4. The match stick is 50mm long.

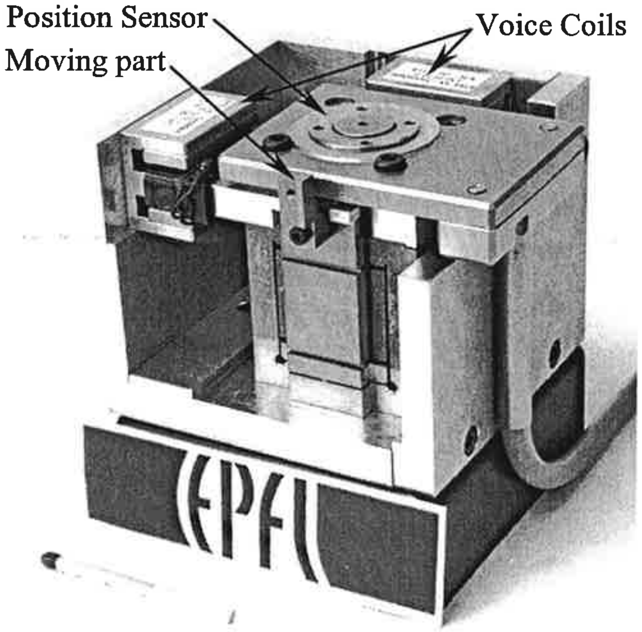

Fig. 6. XY monolithic flexible stage of fig. 5 with two voice coil actuators and an XY optical position sensor. Motion range: ±1mm. Resolution: 1μm.

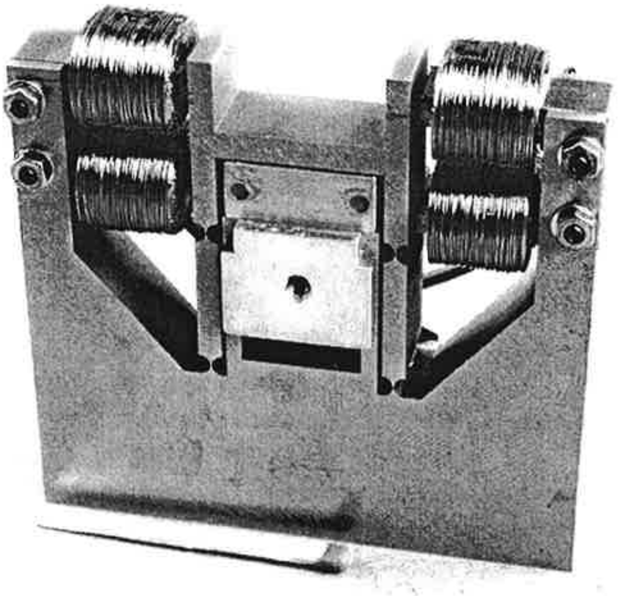

Fig. 7. Translation flexible stage with reluctant electromechanical actuators and eddy-current proximity sensors. Motion range: 1mm. Resolution: 1μm. Very high dynamical properties.

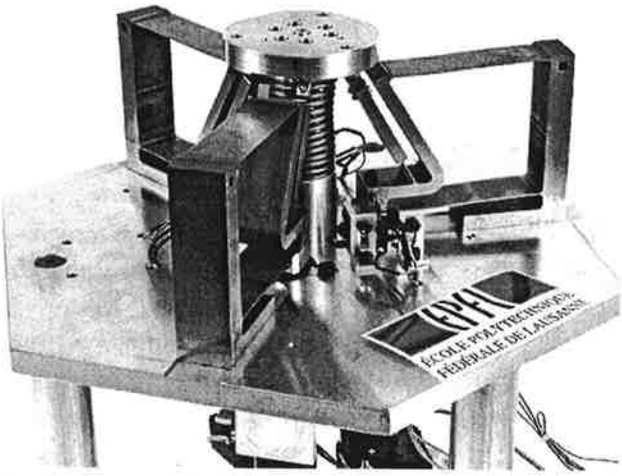

Fig. 8. Orion θX θY Z robot. This parallel robot is composed of three monolithic arms (tempered steel) connected to the moving platform on top. Each arm is actuated by a screw-nut system and a DC motor with encoder. The resolution of each axis is better than 0.8μm. The linear motion range of the robot is ±5mm, the angular motion range is ±7°. (The EPFL sticker is 60mm long).

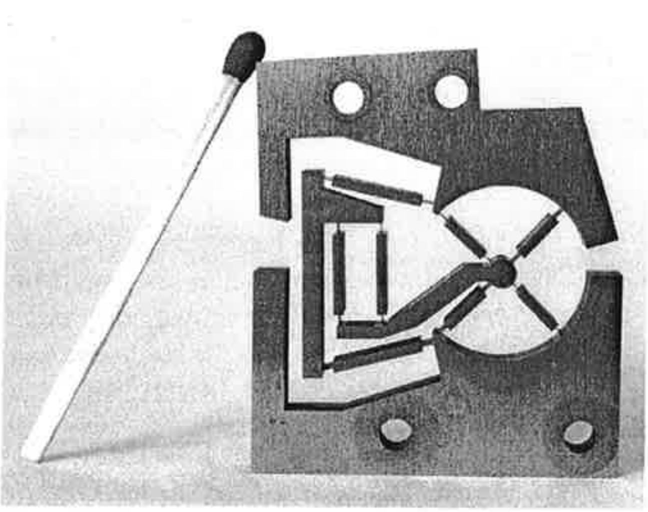

Fig. 9. Long stroke planar flexible pivot with enslaving mechanism. Motion range: ±15°; radial stiffness: 5.3N/µm; radial stiffness without enslaving mechanism: 0.6N/µm.

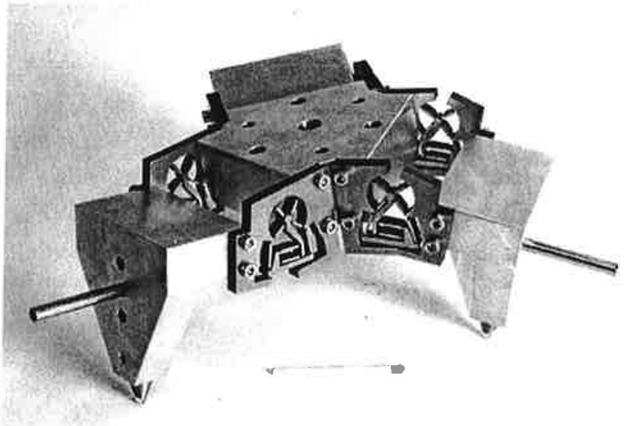

Fig. 10. Mechanical structure of the Tribias six DOF parallel robot.

5. Experimental work.

As explained before, the limited range of motion of flexible bearings calls for flexures of very thin cross sections. We have also seen that wire-EDM is the perfect tool to manufacture flexible parts with micrometric cross-sections. But it must not be forgotten that the juxtaposition and overlapping of the minute craters due to the individual sparkles during the EDM process modify the roughness and the material just below the surface.

One of these modifications is the apparition of an irregular "white layer" which probably influences the joint's behavior. Figure 11 shows the middle section of a 8µm thick circular flexure hinge machined by wire-EDM. The piece was polished and then etched with picric acid to reveal the "white layer" which can clearly be seen on each side of the joint. The thickness of the white layer has been evaluated to vary between 1µm and 2.5µm in this particular case.

The layer making the junction between the "white layer" and the bulk material also has its structure and hardness modified by the high thermal stresses it endured during the sparkling process. It is called the "thermally affected zone" or the "transformation zone".

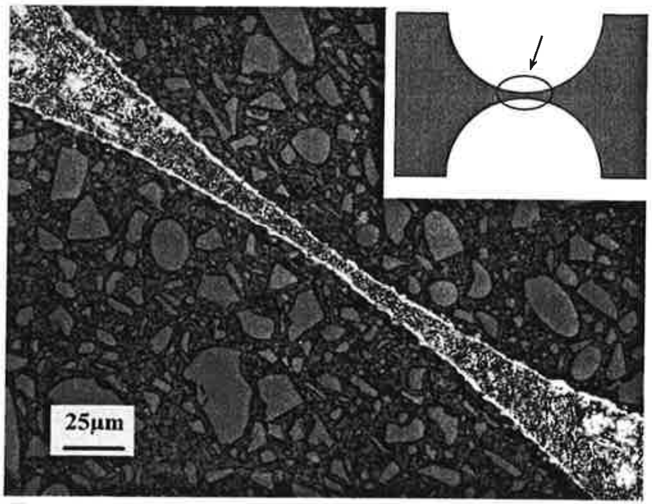

Fig. 11. "White layer" on the central part of an 8µm thick circular flexure hinge. The joint was wire-EDM machined in steel (DIN 06SiCr7). It has a surface roughness Ra of 0.3µm.

When the thickness of the joints is reduced to the point of becoming of the same order of magnitude as the thickness of the thermally affected layers, then the latter cannot be neglected anymore. These modifications have to be taken into account in the theoretical model used to calculate the dimensions of the joints.

We have started studying experimentally very thin flexures by doing stiffness [4] and fatigue [5] measurements on circular flexures hinges 20µm to 50µm in thickness made of high strength carbon steels (DIN 60SiCr7 & DIN X220CrVMo13-4), Perunal aluminum (DIN AlZnMgCu1.5) and Bronze (DIN CuNi15Sn8).

Figure 12 shows the test-specimens used for the fatigue measurements. They have been designed in such a manner as to test simultaneously 11 circular flexure hinges. These hinges are fixed at one end and connected to rigid links at the other end. The rigid links are connected to the moving bloc of a parallel spring stage which is moved back and forth by a cam. Figure 13 shows the whole test bed which drives the test-specimens at 100Hz. Electrical contacts allows to detect the failure of the tested hinges.

So far, the realized measurements [5] showed that for steel (DIN X220CrVM013-4) and bronze (DIN CuNi15Sn8) the fatigue limit of the tested hinges (for 10^7 cycles) is at least as high as the fatigue limit of standard test-specimens tested by the producer of the material.

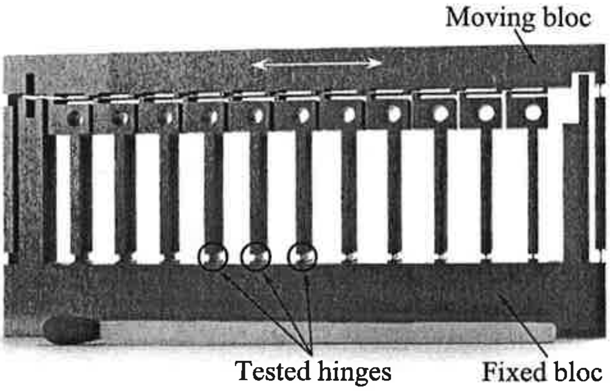

Fig. 12. Fatigue test-specimen (the match stick is 50mm long)

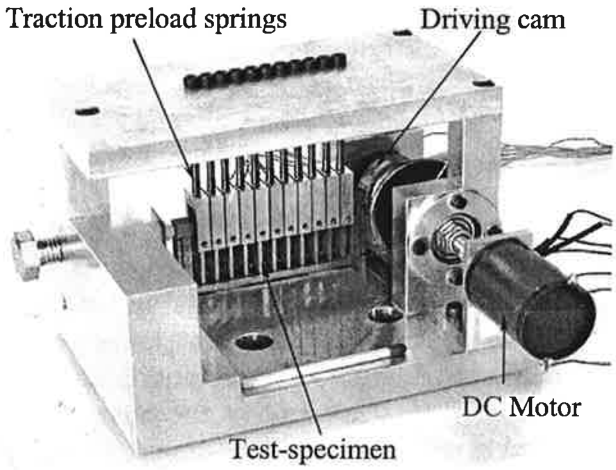

Fig. 13. Fatigue test bed.

6. Conclusion

Flexible joints are known since a very long time, but they still have scarcely been used to articulate the complex mechanical structures of robots having several degrees of freedom.

We are convinced that the sound use of flexible articulated structures will give rise to a new generation of very high precision robots. We hope that the several original examples presented in this paper will convince the reader that flexures have a great unexploited potential; hopefully it will encourage him to study them in more details.

Acknowledgments

The authors are grateful to the company AGIE S.A. CH-6616 Losone, which gave them access to wire-EDM machines for the realization of all the monolithic flexures presented in this paper.

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