Robotica (1997) volume 15, pp 417–420. Printed in the United Kingdom © 1997 Cambridge University Press

Design of parallel robots in microrobotics

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SUMMARY

During the past few years, there has been an increasing demand in the field of precision engineering for fine motion in multi-degrees of freedom systems. These applications motivated the development of a new robotics field called microrobotics. In this paper, we review both the design guidelines for microrobots and the advantages of using parallel robots in very high precision applications. Parallel micromanipulators using elastic joints as well as structures manufactured in single solid and metallic bellows are introduced.

KEYWORDS: Parallel micromanipulator; High precision; Stiffness; Elastic joint; Monolithic structure; Metal bellows; Compliance.

I. INTRODUCTION

Recent improvements in the fields of microstructures, micromechanic devices, microelectronics and optics have allowed the development of microsystems and integrated optical elements. These small size, high technology products require robots capable of manipulating and assembling micro-components with high precision (typically 0.1 μm) and having a workspaces of approximately 1 cm^3. These microrobots also have to be flexible to adapt to different microassembly tasks as well as modular to be easily combined with other manipulators. In certain cases, it is also important for several axes to have passive compliance.

In order to obtain the required submicronic accuracy, the body of these micromanipulators are constituted of a high-precision mechanical structure which is free from backlash, friction and hysteresis. The body should also have a high structural frequency and be both rigid and compact.

In microassembly we define microrobots by their precision, not by their overall dimensions. They are different from micromachines.

The great possibilities of parallel robots in micromanipulation are presented in this paper. Architectures using elastic articulations that are directly cut into the mass are discussed. Certain concepts of microrobots with metallic bellows and a micromanipulator for the coupling of single mode-optic-fibers to waveguides, are also shown.

II. DESIGN GUIDELINES FOR MICROROBOTS

The design guidelines for microrobots are as follows:

- to shorten the kinematic loops to reduce vibration, deformation and thermal dilatation of the structure, and to maximize its stiffness.
- To minimize the length of the line of the force.[1] When a force acts at some point in the machine, it is transmitted through its links and an opposed reaction force appears, which creates deformations. The shorter the line of force, the smaller the deformation.
- To have a direct endpoint position and orientation measurement.[2] It is important to make a full kinematic state measurement directly at the endpoint of the manipulator and use the resulting error signal to correct the position and orientation of the end effector. By using such a measurement, all deflections, backlash, and other error producing realities of the manipulator are lumped into one set of measured variables. In this case, the accuracy of a robot would theoretically be limited only by the measuring device and by the motion resolution of the robot. Sometimes it is possible to use a functional signal like for example, optical transmission in optical microassembly for the coupling of single-mode fibers to waveguides.
- It is also necessary to minimize heat deformation to realize a high-precision machine.[3] Heat deformations cannot be neglected in the microrobotics field.

The arrangement in series of segments or of discrete stages, each giving a degree of freedom, produces an accumulation and an amplification of errors.[4,5] These devices may be modular, but they rapidly become voluminous. Moreover we have a non-uniform distribution of the load on the differents actuators, and gravity alone can produce large deformations.

In the literature we find several suggestions to increase precision and stiffness by reduction of the deflection in the robot structure: active stiffness control,[6] accounting for the deflections at the kinematic modeling level,[7] a local support concept[8] or bracing strategies.[9] These solutions are rather delicate, complicate the control, and can reduce the flexibility.

Another solution aimed towards increasing the stiffness of the structure without increasing its mass is the utilization of parallel robots.

III. PARALLEL ROBOTS AND FLEXURE JOINTS AS SOLUTION

Parallel robots are already used in several applications including assembly,[10,11] transfer of light objects and machine tools. Parallel robots are well adapted to very high precision applications like micromanipulation.[12] These robots are characterized by the fact that more than one kinematic chain links the robot's base to its end effector (gripper or tool). Modularity, symmetry, precision, stiffness, actuators fixed to the base, rapidity, and lightness are their main advantages.

The utilization of parallel architectures for microrobots requires articulations and transmission elements free from backlash, friction, and hysteresis. For this purpose flexure joints are used because they provide articulation without relative motion (rolling or sliding motion between different elements).

These articulations are bent elastically. By electro-discharge machining, different types of elastic joints (revolute, prismatic, universal, or spherical) can easily be manufactured[13] (Figure 1). Most of these joints are based on the elastic beam joint,[14] or the double notched elastic joint.[15] For best performance, the two links and the joint should be formed as one continuous body. Using this monolithic methodology we:

- avoid distortion of clamping points,
- limit the effects of component's assembly and construction inaccuracies,
- have a decisive axis location and
- improve and facilitate manufacturing.

Selection of materials: To have large motion ranges it is necessary to choose materials which allow great elastic deformation without undergoing damaging plastic deformation. These materials have the greatest ratios between the elastic limit and the elastic module: σ/E. Table I shows some well suited materials for this purpose.

Geometry: The joint should be designed to give the required compliances in the direction of bending (low stiffness) and in the directions of restricted motion (very high stiffness) in order to obtain an adequately high compliance ratio. For example, a single beam cannot make a good pivot because the torsional stiffness with respect to the beam axis is low. The solution is to combine two or more beams to create the cross flexure[16] or the unseparated cross flexure.[17]

The reduction of stress concentrations due to geometry or clamping is also important. To avoid fracture it is judicious to place mechanical stops to restrict the motion range.

It should be kept in mind that articulations using material elastic deformation have a few disadvantages: weak displacements, often complex simulation with finite elements, linearity problems, changes in strain according to the joint position and non fixed rotation centres.

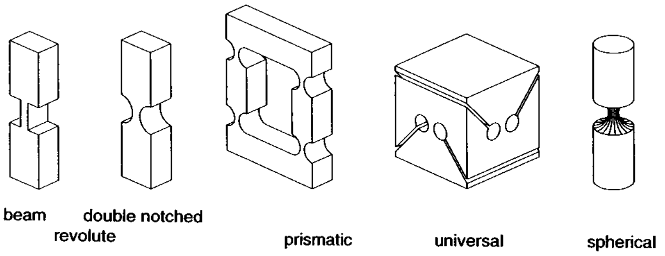

Fig. 1. Typical examples of flexure joints.

Table I. Materials with good elastic properties for flexure joints.

Materials	E (GPa)	σ (GPa)	σ/E
Tempered steel	210	1	0.0047
Perunal (Al–Zn–Mg–Cu)	72	0.48	0.0066
CuBe 2	126	0.75	0.006
Alloys of Ti (Ti–Al–V)	109	0.9	0.0083

IV. PRACTICAL REALIZATIONS

1. *Orion microrobot*

For the coupling of arrays of optical fibers a three Degrees Of Freedom microrobot [θX, θY, Z] has been developed.[18] It uses a kinematic configuration similar to the one described by Lee [19] (Figure 2). The motorization of this structure is insured by 3 linear actuators of the Inch-Worm type, moved by piezoelectric elements. The motion ranges of this structure are ±5 mm and ±2.5° for the two rotations. Each kinematic chain is machined in a single block of steel, which is cut into a parallel leaf spring for the bearing of the actuator, an elastic beam joint for the lower pivot and two crossing beams for the upper spherical joint. The whole of the robot is constituted of 3 of these arms linked to the moving platform (Figure 3).

The next step would be to make a totally monolithic structure in order to get rid of assembly operations. Rigidity would be maximal and the precision excellent.

The advantages of this monolithic robot would be numerous in its realization as well as in its characteristics. This concept benefits from new high precision manufacturing techniques and from the advantages of parallel robots, in which the structure is actuator-free.[12]

2. *Structures with metallic bellows*

Parikian[20] suggests a new microrobot concept which utilizes metallic bellows (Figure 4). These elements allow movements in all directions except for rotation with respect to the bellows axis. They also have the advantages of elastic structures. If we place the bellows

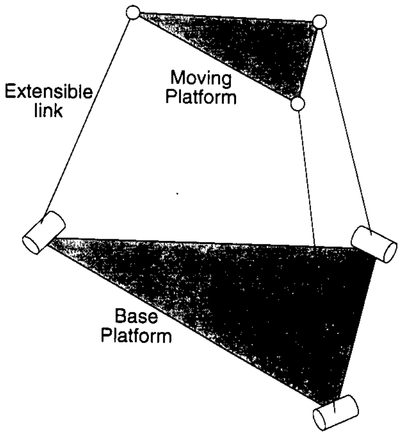

Fig. 2. Lee's kinematic configuration close to Orion's.

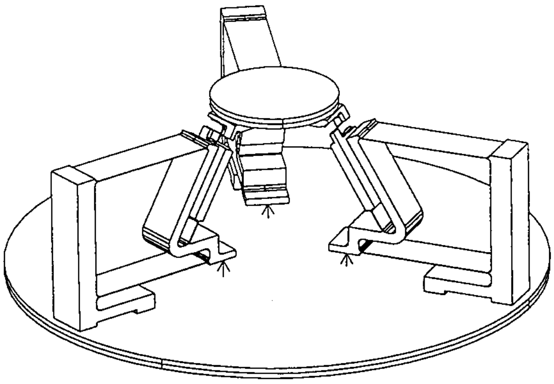

Fig. 3. Orion's 3 DOF [θX, θY, Z] structure.

following 3 perpendicular axes and activate the mobile part with linear actuators from the inside of the bellows, we obtain the 3 translation DOF (like the Delta Robot).[21] Each bellows prevents a rotation. The rigidity of the system is given by the bellow characteristics (materials, diameter, number of undulations . . .). It is possible to add an extra DOF to each kinematic chain by putting an active rotation (with respect to the bellow's axis) at the base of each bellow. In this way a modular microrobot with up to 6 DOF can be made. The rotations are transmitted to the mobile part through the bellows. For small motion ranges the DOF of translation and of rotation are uncoupled from each other. The number of DOF may be adapted according to the task. It is a hybrid structure combining flexible elements (bellows) with traditional bearings (actuators placed inside the bellows). The bellows isolate hermetically the actuators from the outside environment allowing the use of the robot in an aggressive environment as well as in a white room which must not be contaminated by dust emanating from the actuators. For the large elongation of the bellows, the deformation force is compensated by regulating the pressure inside the bellows.

3. Micromanipulator for coupling of single mode fibers to waveguides

One of the current concerns of microrobotics is the reconciliation of submicronic precision with relatively large working space (1 cm^3): one is often obtained to the detriment of the other.

The automation of the coupling of single-mode fibers to integrated waveguides[22] requires the control of 5 DOF (0.1 μm resolution) with only one mobile part (fiber). The approach of the two components is made along two axis (Y–Z) with large travel (>1 cm). We chose a 6 instead of 5 DOF structure, because it has the advantage of being symmetric and usable for other microassembly applications. The developed micromanipulator uses Tsay's architecture[23] with one pivot and one spherical joint per chain, instead of two universal joints (Figure 5). This micromanipulator with an overall size of 4 cm^3 is driven by three Y–Z piezoelectric micro-translators (2 DOF). The three DOF [X, θY, θZ] are produced by relative variation of the microrobot's feet positions. The motion ranges are ±5 mm for the X axis, ±2.5° for the two rotations [θY, θZ], and theoretically unlimited for the [$Y, Z, \theta X$] DOF (in fact, they are limited by the motion range of the two DOF microtranslators). The pivots are plain bearings and the spherical articulations are made of pin tips in conic holes (Figure 6).

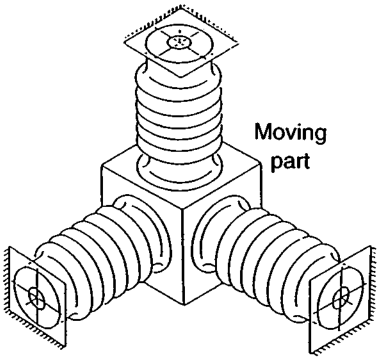

Fig. 4. Bellow's 3 DOF [X, Y, Z] structure.

The next objective is to build this microrobot with flexure joints.

V. CONCLUSION

After reviewing microrobotics' guidelines we have presented the principal features of parallel robots and flexure joints. The Orion prototype showed the potentialities for the future of a totally monolithic structure. We described the possible uses of metal bellows in microrobotics and a microrobot for optical assembly.

These examples have clearly demonstrated the efficiency of the association of parallel architectures with solid flexures.

Several architectures of parallel robots which are solicited in macroscopic applications might be adapted for microassembly tasks. Microrobotics is a quickly developing field which presently conditions the development of numerous domains such as microsystems, integrated optics elements, as well as certain applications like biotechnologies and microsurgery. We have showed that parallel robots have an ever-growing part to play in microrobotics, even if we still find them at the second place in traditional robotics.

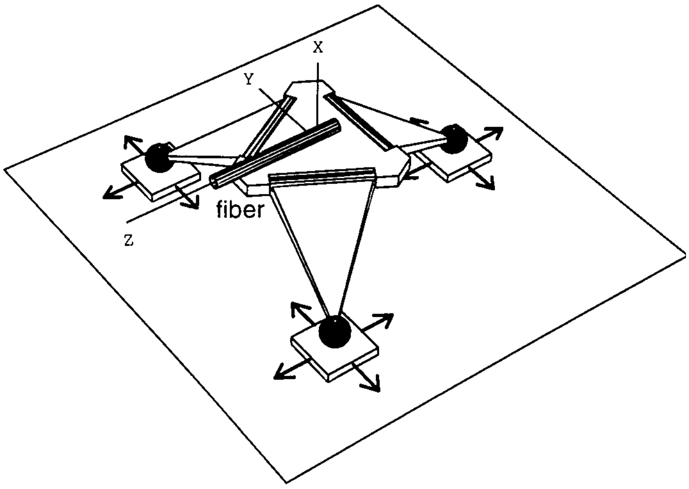

Fig. 5. 6 DOF kinematic structure for optical assembly.

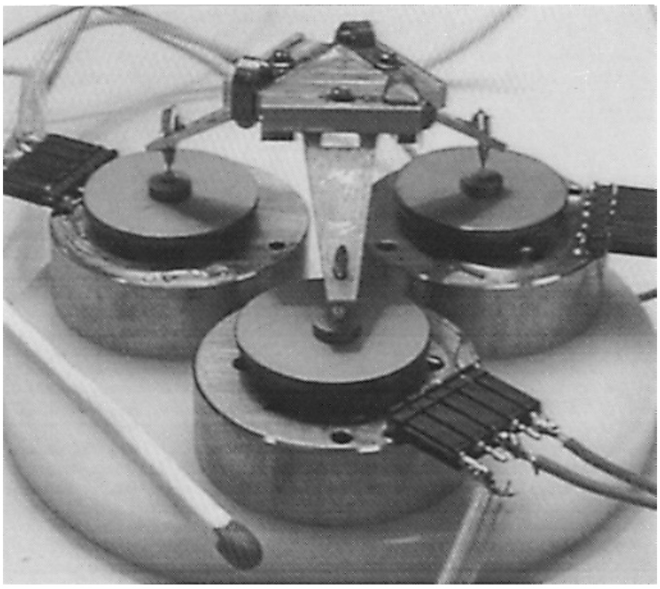

Fig. 6. Micromanipulator prototype for optical assembly.

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