Dynamic Performance of Micro-Compliant Platforms: Experimental Analysis

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Abstract: *In this paper, some basic dynamic characteristics of two micro-compliant mechanisms (one planar, spatial the other) have been analyzed both theoretically and experimentally. The theoretical models have been built by using the well-known elementary concentrated parameters, namely, springs, masses, and viscous dampers. Optical methods allowed to acquire the end tip platform free response to a given initial displacement from the equilibrium position. Each micro-manipulator has been simulated by two simplified models, having, respectively, one and two degrees of freedom (D.O.F.). According to the experimental evidence, the 2 D.O.F. models seem matching the real systems better than the 1 D.O.F. ones. Results have been useful in the real systems parameter identification, which is useful in design (structure and material selection) and simulation (multi-body dynamic analysis).*

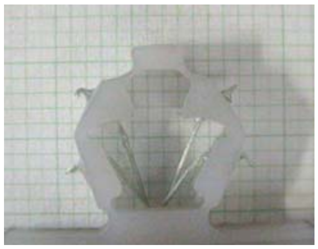
Keywords: *Micro-manipulators, Experiment, Dynamics, Modeling, Materials*

I INTRODUCTION

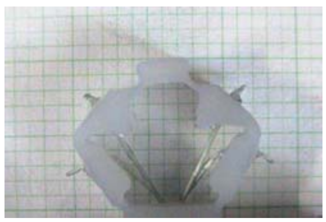
The recent progress in micromachining has enlarged the designer capability of creating new micro-manipulators for various applications, such as, the endoscopy and micro-surgical ones. Among the newest systems, the micro-compliant ones have the advantage of being easily created, without the addition of kinematic pair components. Such particles are even more difficult to be machines because they are much smaller that the characteristic dimension of the micro-manipulator.

Generally speaking, a compliant mechanism consists of a single block whose some portions can be shaped in such a way to present selective compliance due to geometry. Each portion can assume such particular a form that only one or few degrees of relative motion are allowed to the portion ends with respect to each other. The basic principles of compliant mechanism motion, in relation of the applied actuating forces, have been studied for more than a decade [1-4].

The Authors of this paper have been also involved in the development of compliant and micro-compliant mechanisms [5-6]. For example, a planar micro-manipulator prototype has been build, as shown in Figure 1, and studied in [5].



(a)



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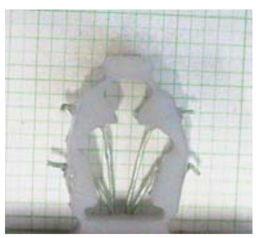


(c)

Figure 1
A view of the planar micro-manipulator in the neutral (a), a lower (b) and a higher (c) configuration

Other spatial micro-manipulators have been suggested in [6], where the platform depicted in Figure 2(a) appeared. This mechanism is composed of three compliant legs that are remotely driven by tendons. In particular, two cables actuate each leg in such a way that the whole set of cables may control the platform configuration. Figure 2(b) shows the corresponding finite element model, which has been used to simulate the static behavior of the manipulator.

Figure 2(a)
A view of the spatial micro-manipulator

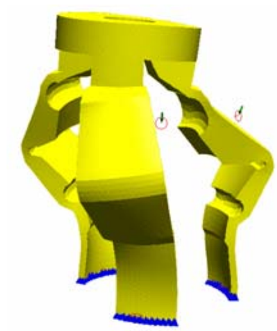


Figure 2(b)
FEM model of the manipulator depicted in Figure 2(a)

II PROBLEMS ARISING IN THE CONTROL OF REMOTELY TENDON DRIVEN COMPLIANT MICRO-MANIPULATORS

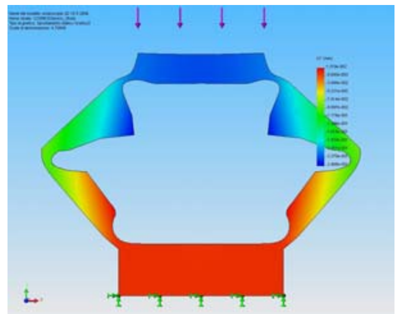
In absence of forces, the system assumes its neutral configuration. In many cases, depending on the attachment points of the three lowest cables, the undeformed position is the highest one, so a given pre-load can be applied to each cable to allow the platform to rise up, if needed. The pre-tension has also the advantage of improving the acceleration capacity of the whole actuated system. In fact, rubber or plastic materials give to the compliant mechanisms some attitude of responding to control with delay. This drawback is tolerable for quasi-static applications, but could be unbearable in dynamic applications. For this reason, the present investigation is mainly dedicated to the measure of this delay and, particularly, to the free response to a given initial displacement from the equilibrium position.

Young's module E	2.1 GPa
Poisson's coefficient	0.4
Density	1.125 10^3 kg/m^3
Yield strength	40 MPa
Ultimate strength	40 – 70 MPa
Elongation	50%

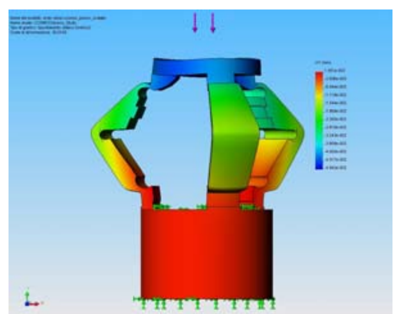
Table 1
The material main characteristics

III STATIC ANALYSIS

The overall structure stiffness can be expressed as the ratio of the force acting normally to the end platform by the platform vertical displacement. This measure has been carried out by simply applying an equal force to the three highest cables, and then measuring the displacement.
For the sake of the parameter identification, FEM models have been build in such a way that the vertical displacement could be easily evaluated along the vertical direction.
The adopted material (nylon) parameters have been reported in Table 1, and an overall constant of elasticity of about 4 10^3 N/m has been found out for both the planar and the spatial system. The FEM results are reliable within the hypothesis of small deformations, and so some little discrepancies have been found between the experimental and calculated values. Some results are depicted in the Fig. 3 in the planar (a) and spatial (b) case.



(a)



(b)

Figure 3
Vertical displacements in the case of 2D (a) and 3D (b) model

IV DYNAMIC ANALYSIS

The two manipulators have been modeled by means of finite elements analysis. This has allowed a straightforward analysis of the static characteristics of the manipulator. For example, a simulation of non symmetric force distribution on the tendons has allowed to appreciate the platform capability in changing its orientation within a range of about 50°. The solid model used in the *finite element analysis* can be exported to commercially available routines, often referred to as *motion routines*, which are able to perform dynamic simulations. However, in the case under study, there are elastic joints that are not easy to be mathematically described and the multi-body parameters need long and non automated work to be defined. Furthermore, the lack of information on the material damping characteristics, such as, for example, the internal viscous or hysteretic damping, is a rather serious one. For this reason, a more simple approach has been used, by restricting the analysis to the platform vertical position, and by, firstly, assuming a one D.O.F. model, as the one represented in Figure 4(a).

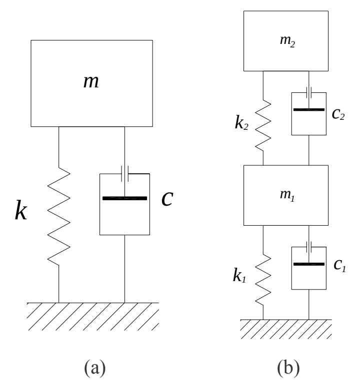


Figure 4
A schematic representation of the adopted models, having one (a) and two (b) D.O.F

In this approximated system, the mass *m* has been simply expressed as the platform mass and the elasticity constant *k* has been evaluated both experimentally and by means of the FEM analysis, with good numerical correspondence. The viscous damping coefficient *c* has been assumed as the free variable to be optimized.

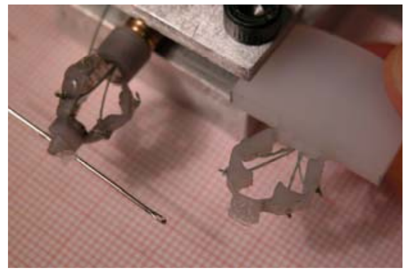


Figure 5
A view of the spatial and planar micro-manipulators

Then a first series of tests has been carried out for both the planar and the spherical manipulators, represented in Figure 5, and the platform end tip vertical displacements have been recorded as a function of time, for an assigned initial displacement and null velocity.

Results have been reported as bullets in the diagrams of Figures 6 and 7. An amazingly high delay of some seconds is required by the system to return to the neutral position. This means that the system response to a control signal may be very critical when the command's goal is the platform rising.

As for the simulation, the first model gave imperfect results, as the dashed lines show in the Figures 6 and 7. The solution has been analytically achieved by integrating the simple state dynamic force balance equation for the mass *m*, in the case of non periodic solution.

A more detailed model of the manipulator can be obtained by considering that there are two links for each leg that sustain the platform (in both the spatial and planar manipulator). Hence, it has been assumed as reasonable the adoption of two masses for each manipulator, as representative of the inertial contents.

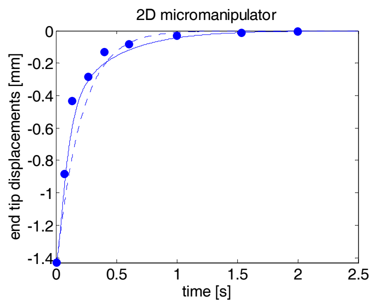


Figure 6
Time history of the planar manipulator platform position, from initial null velocity and initial displacement equal to 1.43 mm

The schematic 2 D.O.F. model has been represented in Figure 4(b), where there are also two viscous dampers and two elastic springs. In particular, the two masses m_1 and m_2 have been evaluated in such a way to preserve the kinetic energy equivalence with respect to the corresponding mobile masses in the system.

The elasticity constants have been evaluated by means of the FEM static force analysis, while the viscous dampers have been assumed as the models free variables. The mass 2 initial position has been assumed as the platform's, while the mass 1 initial position has been evaluated by imposing an initial force balance on the mass 1 itself. Finally, null velocities have been initially assumed for the two masses. The solution have been analytically obtained by solving the fourth order characteristic equation

$$\det(\lambda^2 M + \lambda C + K) = 0 \qquad (1)$$

where M, C, and K are, respectively, the mass, damping, and stiffness matrices, in the case of four real solutions (non periodic motion). Many iterations of the procedure were needed in order to achieve a good esteem of the damping parameters. Finally, results have been reported in Figures 6 and 7, as solid lines.

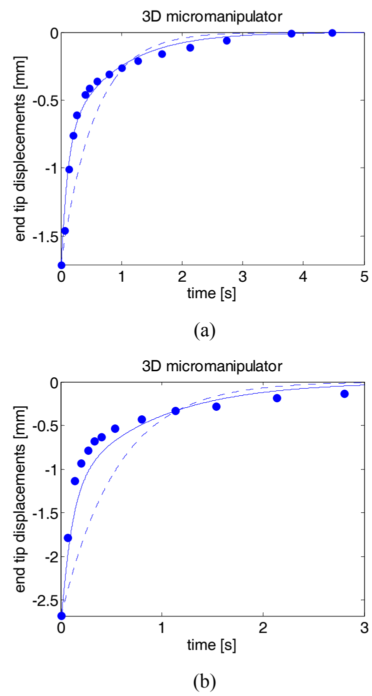


Figure 7
Time history of the spatial manipulator platform position, from initial null velocity and displacements equal to 1.71 mm (a) and 2.68 mm (b)

The 2 D.O.F. model presents a much better concordance with the experimental data. In fact, it is reasonable to assume that the most part of the response delay is due to the upper links of the systems, probably for constructive reasons. Hence, it could be helpful making the upper elastic joints a little more rigid, by shaping the corresponding zone with a bit higher thickness.

V FORTHCOMING ANALYSIS

For the sake of the present application, it is believed that a further series of tests could be dedicated, in a near future, to the approximated measure of the material modulus of resilience, for instance by the Lupke rebound test. For the sake of completeness, we recall that *resilience* is intended as the capacity of a material to absorb energy, when it is deformed elastically, and to recover it after unloading. This material property is not well investigated in rubber or plastic materials, and the behavior of the small part components still remains uncertain.

Conclusion

The experimental tests have shown a surprisingly high delay in the response of the platform positioning system with respect to the control signal, this delay reaching the amount of some seconds! This makes the adoption of compliant micro-manipulators rather critical in all those applications which require high performance in dynamic response. Among the two simply models, the one which is based on a double mass-damper-spring system simulates better the vertical displacements of the platform. This model has been used to achieve a good parameter identification, which is useful in selecting some possible structural variations, such as the joints stiffness, and improving the dynamic response.

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