A Robot for Cell Injection:
Modeling, Design and Experimental Validation

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ABSTRACT

This work deals with modelling and experimenting of a compliant serial-parallel robot. Using Pseudo-Rigid-Body Modelling (PRBM) of elastic structures, a kinematics and stiffness model of a serial-parallel structure has been built. Several approaches for pre-tensioning of a parallel structure with elastic joints were developed in order to eliminate backlashes and improve the performance of its actuators. In this work a robot is designed to inject biological cells with size in the range of 10-30µm. The approaches used for pre-tensioning of the robot have been analysed and subjected to numerical evaluation. Assessing the mechanical parameters of the tensed manipulator has been performed using the following methods: PRBM and Finite Element Analysis (FEA). An experimental set-up for testing a robot prototype has been developed, using an optical system and correlation technique for digital image processing. The experimental results obtained are compared to data received from the numerical experiment.

Keywords: *Cell Injection, Compliant Joint, Digital Image Correlation, Micromanipulations, Serial-Parallel Robot*

1. INTRODUCTION

Many micro- and nanomanipulation processes have been robotized, facilitating the human access to those micro- and nanospaces with unknown dynamics and properties. The process of robotization creates many problems that have to be resolved. One of them is the development of mechanical constructions that are appropriate for controlling the working tool, that can be applied to the domains of microsurgery and microbiology, and particularly to cell manipulations, microelectronics research, chemistry and investigation of thin films, scanning of micro- and nanosurfaces, microassembly etc. (Fatikow & Rembold, 1997; Pernette & Henein, 1997; Kasper & Heinemann, 1998).

The body of these micromanipulators is constituted of a high-precision mechanical structure which is free from backlash, friction and hysteresis, in order to obtain the required submicron accuracy, (Pernette & Henein, 1997). Mechanisms with closed kinematics chains are suitable for high- precision tasks (Li & Xu, 2005;

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Yao & Dong, 2008; Prusak & Uhl, 2009). As it is well-known, parallel kinematic mechanisms possess inherent advantages over conventional serial manipulators, such as high rigidity, high load capacity, high velocity, high precision, etc. The high accuracy of such mechanical systems is due to their inherent structural stiffness. The small workspace in the case of cell manipulations is not to their disadvantage, since it is sufficient for the application under consideration.

On the other hand, compliant mechanisms, i.e., flexure-based mechanisms can be employed into parallel mechanisms for high-precision applications (Li & Xu, 2005; Yong & Lu, 2008; Yong & Lu, 2009). Compliant mechanisms exhibit many advantages in terms of vacuum compatibility: they have no backlash property, nor nonlinear friction, and what is more, their structure is simple, and they are easy to manufacture. The use of a compliant mechanism in order to provide motion transfer means that the position accuracy of such micromotion mechanisms depends only on the accuracy of microactuators and on the position sensors. It is possible to use the deformation in the elastic areas to achieve tension in the closed structures as well.

Many actuation principles have been applied to drive the compliant mechanism in micro- and nanorobots. Piezoelectric actuators, electrostatic, electromagnetic and shape memory allow actuators to be utilized to provide fine motions to micro- and nanorobots. Piezoelectric actuators are commonly used to provide fine resolution of input displacements in the subnanometer range (Kasper & Heinemann, 1998; Chu & Fan, 2006; Gao & Swei, 1999; Kasper & Al-Wahab, 2004), since their resolution is dependent solely on the quality of applied voltage signal. Piezoelectric actuators offer substantial advantages for microtechnology applications compared to competitive actuators, e.g. large force, high frequency and small size. Piezoelectric actuators developed in closed kinematical structures are suitable for high-precision tasks in 3D space (Prusak & Uhl, 2009; Ionescu & Kostadinov, 2002). The concept of total decoupling is accepted to isolate and protect the actuators as the presence of unwanted transverse loads may damage some types of motors such as the piezoelectric actuators. Translations in compliant parallel stages, and the design of a totally decoupled parallel micropositioning stages has been proposed (Li & Xu, 2011) in order to eliminate the cross-axial coupling errors between the axes.

The pseudo-rigid-body-model is commonly used (Zhang & Zou, 2002), to predict the displacements of compliant mechanisms with elastic joints. As a rule, it models an elastic joint as a revolute joint with a torsion spring attached. The pseudo-rigid-body method is very effective and it simplifies the model of compliant mechanisms. An analytical model has been created in order to estimate the mechanism stiffness with elastic joints taking into account compliances of elastic joints in all axes (Pham & Chen, 2005).

Various ways exist for evaluating the internal tensions and deformations in elastic systems. One of them is the so-called Finite Element Analysis (FEA) (Li & Xu, 2005; Yong & Lu, 2008; Pashkevich & Chablat, 2009). The FEA method has proved to be the most accurate and reliable, since the joints are modelled with their true dimensions and shapes. The only disadvantage of this method is its high computational expenses.

In recent years, many attempts have been made to leverage robotic technologies in order to facilitate the process of cell injection (Lu & Zhang, 2011; Xie & Sun, 2011). The ability of efficiently injecting drug compounds or biomolecules into individual biological cells, and statistical analysis of their cellular responses is significant for gene injection, intracytoplasmic sperm injection and pharmacology research (Tang & Li, 2012). Robot-assisted microinjection has attracted much interest from both the engineering and biological communities due to its combined advantages of high precision and throughput.

The aim of this work is to create a pseudo-rigid-body model of the robot structure with elastic joints and to develop different approaches for tensioning the parallel structure.

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