Hybrid Micro-Nano Robot for Cell and Cristal Manipulations

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Abstract: The paper presents some Computer Assisted Engineering (CAE) aspects concerning the achievement of a hybrid actuated micro-nano robot. Starting from a unitary concept Control - Design, different kinematic solutions were developed and compared, before a decision upon the structure was selected. Multiple closed loop simulations were performed via MATLAB/Simulink, Solid Dynamics and ANSYS software. The experimental results for the nano-stages/actors were run for two XY orientations with a range of 240 arcsec while and for translation in Z direction in a stroke range of 65μm, and system resolution of 10nm. Additional identification and reconstruction of the hysteresis curves were obtained and implemented in the model by using a Neuro-Fuzzy technique. Two hardware systems were developed for the micro and nano robot respectively. Corresponding software HMI capable also of joy-stick telemanipulation was developed.

Keywords: Robotics, micro and nano actuation, piezo drive, position and speed control, HMI, mathematical modelling, modelling and simulation, solid bodies.

1. INTRODUCTION

Robots for micro and nano manipulations are mostly used in biological and microcomputer research for cellular technology and investigation of thin films, in Atomic Force Microscopes (AFM) and Scanning Tunnelling Microscopes (STM). From a historical standpoint, the manipulators were, at first, man-operated, and then semi-automated. Thus they had a limited accuracy and productivity. For the current state of the art cellular technology, an easier insertion of probes, of electrodes or of a micro-pipette through the membrane of a single cell can only be achieved by using precise high speed steps and the appropriate actuation, a special hardware and a corresponding suitable software.

1.1 The PZT actuation

The classic actuation technologies using an AC or DC electromotor followed by a reduction drive and ball-screw drive cannot achieve the needed speed profile or the accuracy class. The use of a step-by-step electromotor offers better behaviour for low power. On the contrary, for a piezo crystal a large voltage variation corresponds to only a slight modification of physical dimensions. This so called Piezoelectric Technology (PZT) can be used to obtain a high accuracy position of under 1μm.

Another argument for using PZT-positioning is given by its ability to safely operate even in unfriendly strong Electro Magnetic Fields (EMF), for example in Computer Tomography (CT) and Magnetic Resonance Imaging (MRI). Here, the manipulation system is used for applications like: bio engineering and research, for example cell positioning and penetration, tele-operated surgery, exploring micro and nano physics like the construction of nano-structures, handling a micro electrode in quality control tasks, etc.

On the one hand, position precision has to increase (<10nm) as the object size decreases, and on the other hand, the workspace has to have macroscopic dimensions (> 1cm^3) to give high manoeuvrability to the system and to allow suitable handling at the border between the micro and macro worlds. For example, in transgenic applications such as injecting DNA, the insertion of a fine tube through the wall and membrane of a cell requires a fast, highly precise motion in only one the Z direction, with a displacement of 50μm and an angle in the XY plane in the range of milliradians.

In many situations, the total time needed to complete a positioning operation is less than 100ms, and a high average speed is needed. In more restrictive cases, a speed profile is of the essence. Thus, an average speed is not enough, but also how the speed actually evolves as a time function during the operation.

Some applications, for different numbers of degrees of freedom (DOF) and structures are presented in Burleygh (2004), LSS-2100 and LSS-2200 Cell Penetrator Systems, Ionescu et al. (2002) Micro Robots with Stewart platforms structures, or in Kleindiek Nanotechnik (2004), Klocke (1998), a Nano Motor® Tilting Table.

Fig. 1. Flow Chart of CAE-Development (source: F. Ionescu©)

1.2 Applied CAE for a Micro-Nano-Robot

The four stages of the Computer Assisted Engineering (CAE) for the micro-nano robot are dedicated to obtain the highest achievable accuracy range and are depicted in 1. Starting from task formulation encompassing the main ideas, the implementation methodology, a list of performance indicators with desired values, and price margins, a first theoretical study can be started. This is be based upon a (static and dynamic) nonlinear Mathematical Model (MM) given as a System of Coupled Differential Equations describing the operation of the robot, as an input-output system. For the direct dynamics one obtains the following form, after having multiplied on the right side with $[M]^{-1}$:

$$\begin{aligned}\{\ddot{q}_k\} = &-[D]\cdot[M]^{-1}\cdot\{\dot{q}_i\} - [C]\cdot[M]^{-1}\cdot\{q_i\} + \\ &+[A]\cdot[M]^{-1}\cdot\{\dot{Q}_i\} + [B]\cdot[M]^{-1}\cdot\{Q_i\} + \\ &+[E]\cdot[M]^{-1}\cdot\{U_i\}\end{aligned} \qquad (1)$$

with: $i \in [1..6n]$; $k \in [6n-5..6n]$; $[M]$- the inertia matrix {kg or Nms^{-2}}; n - total number of degrees of freedom (DOF); $[D]$- the Damping Matrix { N/(m/s) or Nm/(rad/s)}; $[C]$ - elasticity matrix {N/m or Nm/rad}; $[A]$ – coefficients matrix of the first derivative of the perturbation vector $\{Q\}$; $[B]$ - coefficients matrix of the perturbation vector; $[E]$ - coefficients matrix of the input vector $\{U\}$.

Several static and dynamic nonlinearities characterize the function of each drive axis, the electric motors, amplifiers and sensors. The most common examples that occur for the designed robot are: non-diagonal matrices, nonlinear properties of slides friction and electric saturation properties of the Step Motors and Piezo Actuators. The simulation can be performed using the modelling and simulation (MS) platform. The CAD stage can now be initiated, but a direct Solid Body supported approach could also be helpful. A first prototype can be achieved after a Finite Element Modelling (FEM). It determines displacements and critically stressed regions of parts. This information is useful for optimization. Additionally the eigenvalues and eigenforms are obtained. For research and development purposes a virtual prototyping will be obtained - which is much cheaper and with high accuracy - from the description to the simulation of virtual models. In real cases, after the first prototype is obtained, an experimental setup will help obtain the real behaviour of the static, stationary and dynamic states. In the mean time, the processor is developed: data set is defined and the appropriate control strategy is established to be implemented both in software and hardware.

1.3 Limits of Human Operator

To achieve specific performances using a human operator for micro movement process is quite difficult. And when it is facing with the nano domain, the task is quite impossible. However, this operation really depends on the operator's skills and the efficiency of this task is very low. For example, an intra cytoplasmatic sperm injection implies doing a minute operation with micrometric precision (Sittia and Hashimoto (2000), Sittia and Hashimoto (1999), Kim et al. (2001), Song et al. (2001), Friedt et al. (1999)). In this case the micro-nano manipulator is used to perform physical operations to inject genes, nucleus or embryos. Therefore, the automation of this operation using a flexible robot system drastically improves the achieved effectiveness and accuracy.

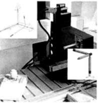

Fig. 2. Real obtained the Micro-Nano-Robot (source: F. Ionescu©)

1.4 The Micro-Nano Robot

To overcome these limits, a nano robot with 6,5 joints was theoretically designed (Ionescu and Kostadinov (2003), Ionescu et al. (2007a), Ionescu et al. (2002), Ionescu et al. (2003a), Ionescu et al. (2004), Ionescu and Talpasanu (2006), Ionescu and Kostadinov (2007)). From the viewpoint of kinematic constraints, mechanical implementation with simulation and appropriate control are significant in practice. This present paper focuses on obtaining a CAE design of the robot as a hybrid micro-nano approach and of its appropriate control. The hybrid nature is determined in two stages, both

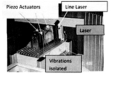

Fig. 7. Nano robot with laser unit for displacement's calibration (source: F. Ionescu©)

3. MATHEMATICAL, SOLID BODY AND FINITE ELEMENT MODELLING AND SIMULATION

3.1 Structure Identification, Experimental Setup

The identified movement was oriented on the X, Y and Z axes of the nano-stages, using different identification methods with two different input signals: sinus and triangle.

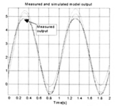

Fig. 8. Sinus displacement (source: F. Ionescu©)

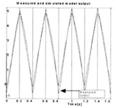

Fig. 9. Triangle displacement (source: F. Ionescu©)

Resulting spring forces have been adjusted using the strain gauge signal in assembly process of all mechanical components by the foreseen adjustable elements. Based on the theoretical and simulated results an experimental set-up (Fig. 6) including a nano robot prototype has been developed. (Fig. 7) The strain gauge sensors are used with a Wheatstone bridge. They operate with DC preamplifier clip module AE101 HBM® (Ionescu et al. (2003a)) for static and dynamic measurements (<6kHz). For data sensor acquisition, a National Instruments NIDAQ LAB PC+ board (Ionescu and Kostadinov (2007)) with the corresponding NI-DAQ 4.9 application software was used. A laser line emitter with differential diode was used to measure and calibrate the position. As a controlled power supply for the piezo actuators with capacitive loads, a PC card power supply NV C1 (Ionescu (2007)) was used.

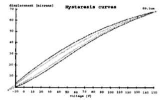

Fig. 10. Hysteresis of the Piezo Actuator PA50/14SG of X and Y (source: F. Ionescu©)

It can drive within a nm resolution up to three axes. The experiments were done using two types of input voltage, sinus and triangle. The experimental results for orientation and translation obtained are in a range of 0-1.10 mrad and 0-65μm, with the nano robot resolution of 10nm. Results on hysteresis of the X and Y axis are presented in Fig. 6 and 7. For both cases the transfer functions has been experimentally obtained, for the same sinus and triangle inputs, using a MATLABR identification procedure, with resampling factor of 0.15, (see Fig. 8, 9) using three experimental /simulated identifications.

Via identification the transfer functions for the axis X, Y and Z were obtained. For the X axis the obtained transfer function for the sinus/triangle input signal is:

$$H_X(s) = \frac{(0.0317s^2 - 0.0287s - 0.003)}{(s^3 - 0.9997s^2)} \tag{2}$$

A comparison of theoretical and experimentally achieved identification results for the transfer functions along the X-axis obtained by Matlab/Simulink identification both for sinus and triangle input signal, the transfer function for X-axis of the nano robot here is shown below:

$$H_{Y,th}(s) = \frac{(0.0307s^2 - 0.0282s - 0.0025)}{(s^3 - 0.9997s^2)} \tag{3}$$

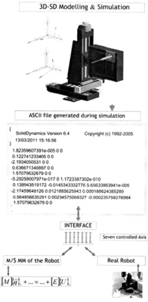

Fig. 17. Control interface in SD and MS (source: F. Ionescu©)

Linear scaling In this case a single corresponding constant is used between the nano/micro robot positions and the macro joystick angular positions: $\varphi_{i,j} : x_{R,i} = \alpha_{s,i} \cdot \varphi_{j,i}$. The human operator has no perception about the robot end-effecter dynamics and the space size in which it manipulates. Hence, in the case of cell micro and nano manipulations a haptic interface has to provide the operator with the feeling that he knows the dynamics of the objects to be manipulated.

Nonlinear scaling It is achieved by introducing a virtual mechanical appropriate impedance $Z_{s,i}$. The robot dynamics can be assigned to virtual couple mechanical impedance Z, appropriately to the operator to manipulate in the micro/nano world, as follows: the macro joystick angular positions de ne the force Fi by which the robot axes will be driven, by: $F_i = z_{s,i} \cdot \varphi_{j,i}$. Thus the teleoperation controller can realize proper coupling between the macro and nano world.

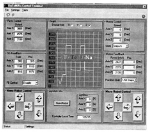

Fig. 18. Control menu of the two robots stages (source: F. Ionescu©)

5.4 Controlling and validating the model

The most important tasks are to find out how stable and high performance in the real conditions the control can be obtained: the human operator, the dynamics environment, time delays in communication channel, hysteresis, etc. For an obtained robotic model, the SDS simulation environment can send the position of all the joints to the real robot. By using an ASCII file, the positions of all the joints relative to time can be imposed on the real counterpart so as to compare both of them simultaneously (Fig. 17). By observing the differences between the real and the modelled robot one can improve the real prototype.

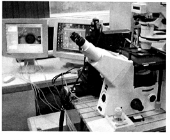

Fig. 19. Experimental set-up for cell penetration (source: F. Ionescu©)

5.5 Experimental Setup

A visual feedback can be obtained by using a Carl Zeiss Microscope Axiovert200 Zeis (2005b) equipped with