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High speed closed loop control of a dielectrophoresis-based system

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Abstract—Nanosciences have recently proposed a lot of proofs of concept of innovative nanocomponents and especially nanosensors. Going from the current proofs of concept on this scale to reliable industrial systems requires the emergence of a new generation of manufacturing methods able to move, position and sort micro-nano-components. We propose to develop 'No Weight Robots-NWR' that use non-contact transmission of movement (e.g. dielectrophoresis, magnetophoresis) to manipulate micro-nano-objects which could enable simultaneous high throughput and high precision. This article deals with a control methods which enables to follow a high speed trajectory based on visual servoing. The non-linear direct model of the NWR is introduced and the calculation of the inverted model is described. This inverted model is used in the control law to determine the control parameter in function of the reference trajectory. The method proposed has been validated on an experimental setup whose time calculation has been optimized to reach a control period of 1 ms. Future works will be done on the study of smaller components e.g. nanowires, in order to provide high speed and reliable assembly methods for nanosystems.

I. INTRODUCTION

This article deals with the closed loop control of a non-contact dielectrophoresis system which can be considered as an original robotic structure compared to the current industrial robot. The first industrial robot UNIMATE [1] based on standard joints was commercialized in 1961 (see figure 1). Nowadays more than one million of robots are in use all over the world. In the 1980’s the use of compliant structures in robotics [2] was started to enable high precision positioning making them, at present, the most widely used structure for microscale robots [3], [4]. However, transmission of movement in such robots is obtained via the movements of mechanical parts which largely limits throughput due to inertial effects. In the 2000’s, LightWeight Robots [5], [6] have been developed by KUKA[7] to reduce robot inertia. However, the impact of inertia is still important in the small scales (micro-nano) where the inertia of the object is highly negligible compared to the one of the robots. A new consist in developing robots that use non-contact transmission of movement to manipulate micro-nano-objects [8], [9], [10]. Besides eliminating the inertia of a robotic structure, this approach also eliminates friction and adhesion (between the tweezer and the component) which highly reduce robot performance and life time.

These 'No Weight Robots’ NWR are at the cross-road between parallel robot and current non-contact manipulation.

Firstly, NWR consists of moving components by applying forces coming from several physical field sources which have a similar effect to parallel robotics [11], [12] where the platform is moved by several mechanical forces coming from several robotic legs. The use of non-contact forces, rather than mechanical forces, changes the robot design drastically. In this regard, existing robotic approaches cannot be transferred to NWR. Secondly, current non-contact manipulation has been achieved mostly by open loop for object positioning or self-assembly [13-20]. The only exception concerns laser trapping which has been experimented in closed-loop by Arai et al. [19], [20]. However, laser trapping induces forces around tens of picoNewtons limiting the achievable throughput. The dielectrophoresis proposed in this paper generate forces around thousand times higher [21], [22]. Providing closed loop control strategies will enable active and reprogrammable trajectory control and guarantee the final position of a manipulated object.

This paper introduces a numerical model of a micro-bead’s behaviour in a dielectrophoresis system, in the next section a closed loop control strategy is presented then the experimental setup is presented as well as experimental results.

II. DIRECT DYNAMIC MODEL OF A DIELECTROPHORESIS-BASED SYSTEM

In this section, we present a 3D dynamic model of a bead driven by a dielectrophoretic force. This model is used in the trajectory control law to determine the voltage to applied in function of the trajectory reference. As we consider only beads and no dephasing, electrorotation is not considered.
A. Dielectrophoresis force simulator

In order to compute the electric field and then the dielectrophoretic force applied to a micro-object in an electrode structure, a numerical simulator is needed. This numerical simulator must be able to compute the dielectrophoretic force generated by very complex geometries in a very short time. For one hand, corresponding analytic equations are very complex and hard to be established. For a second hand, the finite element modeling (FEM) solution is limited to a long computation time and specially when electric voltage changes frequently. Thus, we propose to use the hybrid numeric simulator proposed in [16] gathering the ability of the FEM solution to simulate complex electrodes geometry and the short computation time of the analytical equations. According to [23], the dielectrophoretic force $\vec{F}_{DEP}$ applied to the micro-bead’s center $X(x,y,z)$ with respect to the electric field $\vec{E}(X,U)$ can be written as:

$$\vec{F}_{DEP}(X,U) = 2\pi\epsilon_0 r^3 Re[K(\omega)]\nabla(\vec{E}^2(X,U)), \quad (1)$$

where

$$K(\omega) = \frac{\epsilon^* - \epsilon_m^*}{\epsilon^* + 2\sigma \epsilon_m^*}, \quad (2)$$

and $\epsilon_p^*$ and $\epsilon_m^*$ are respectively the complex permittivity of the particle and the medium with:

$$\epsilon^* = \epsilon + j\frac{\sigma}{\omega}, \quad (3)$$

$\epsilon$ is the relative permittivity, $\sigma$ is the conductivity and $\omega$ is the angular velocity of the electric field. Thus, if we consider a configuration of $n$ electrodes, by applying $n - 1$ sinusoidal electric voltages identified by their magnitudes $U = [U_1, \ldots, U_{n-1}]$ and there angular velocity $\omega$, the electric field $\vec{E}(X,U)$ can be computed using the hybrid method described in [16]. This hybrid method consists in computing the electric field $\vec{E}(X,U)$ by integrating the surface charge density on the electrodes. In fact the electric charge density $Q$ and the magnitudes of the applied voltages $U$ on the electrodes are linearly related:

$$Q = \sum_{i=1}^{n-1} C_i U_i, \quad (4)$$

where $U_i$ is the magnitude of the applied voltage on the $i$th electrode and $C_i$ is the elementary inter-capacitance between the electrodes influenced by the $i$th electrode. The inter-capacitance between the electrodes depends only on the geometric shape of the electrodes and the electric permittivity of the medium. The $C_i$ is computed analytically with respect to the applied voltages $U$ and the elementary inter-capacitances $C_1$ and $C_3$. The figure 2(c) shows how the electric charge density $Q$ is analytically computed with respect to the applied voltages $U = [75V, 0, 75V]$ and the elementary inter-capacitances $C_1$ and $C_3$.

Once the matrix of the electric charge density $Q$ is computed, the electric field can be calculated analytically in a point $X(x,y,z)$ in the medium. In fact, with each value $Q_{i,j}$ of the computed matrix $Q$ corresponds a $x_{i,j}$, $y_{i,j}$ point on the electrodes ($z_{i,j} = 0$ because of the electrodes are in the $x,y$ plane). Thus, the expression of the electric field $\vec{E}$ at the point $X(x,y,z)$ is:

$$\vec{E}(x,y,z) = \sum_{i} \left( \sum_{j} \frac{Q_{i,j} r^3}{4\pi\epsilon_m r^3} \right)$$

where $r = [x - x_{i,j}, y - y_{i,j}, z]$, and the DEP force can be also computed analytically with respect to (1). The figure 3 resumes the DEP modeling simulator (DMS) block. The block’s inputs are the geometric shape of the electrodes, the applied voltages and the micro-bead’s current position. This block generates the computed $x$, $y$ and $z$ components of the dielectrophoretic force applied to the micro-bead in its center.

B. 3D direct dynamic model

The inertia of a micro-bead in a dielectrophoretic force field can be neglected [9], [10]:

$$\vec{F}_{DEP}(X) + \vec{F}_{Drag}(\dot{X}) + \vec{P} = 0. \quad (6)$$
In the micron scale the Stokes approach of the viscosity friction is valid, \( F_{\text{Drag}}(X) \) becomes:

\[
\overrightarrow{F}_{\text{Drag}}(X) = -6\pi\nu R \overrightarrow{X},
\]

(7)

where \( \nu \) is the dynamic viscosity and \( R \) the radius of the micro-bead. The dynamic equation is thus:

\[
\overrightarrow{X} = \frac{\overrightarrow{F}_{\text{DEP}}(X) + \overrightarrow{F}}{6\pi\nu R} = \frac{\overrightarrow{F}_D(X)}{6\pi\nu R},
\]

(8)

where \( \overrightarrow{F}_D \) is the driving force, sum of the dielectrophoretic force and the weight.

The diagram in the figure 4 illustrates the 3D direct dynamic modelling. Having the applied electric voltages and the electrodes geometry as input, the direct modelling simulator computes the corresponding micro-bead’s trajectory. In generally, the micro-bead’s behavior in dielectrophoretic force field is characterized by its high dynamics and non-linearity. This numeric simulator is experimentally validated in [16] where we have shown that the dynamics of the micro-bead is less than \( 3\text{ms} \). Moreover the behaviour of the micro-bead is subjected to a high nonlinearity and especially when the micro-bead approaches the electrodes.

III. HIGH SPEED CONTROL STRATEGY

As mentioned above, the dielectrophoretic-based system is characterized by the high speed motion of the micro-object, which makes it compatible for a high speed control system. Thus to use the dielectrophoretic force to control the position of a micro-object in such system two main aspect must be considered. The first one is the high speed of the micro-object’s motion, where the control system must be theoretically at least twice faster than the time constant of the system. The second one is the high non-linearity of the generated force with respect to the applied voltages and the micro-object’s position. For these reasons, classic control low, such as PID controller are not efficient. In this study we propose to consider the dielectrophoretic system as a robotic manipulator where the dynamic model presented above is the direct dynamic model (DDM). The inverse dynamic model will be used later to control the micro-object’s velocity and position. The computation of the DDM presented in (4), (5) and (8) is quite long and it takes several milliseconds even when using a high-speed computing processor, e.g. if we use a \( 1MHz \) control system, at least \( 10^4 \) CPU clock are needed, which mean that \( 10\text{ms} \) required to complete the computation. In order to improve the calculation time in the controller a 3D simplified model has been developed.

A. 3D simplified model

In order to reduce the complexity of the computation, we will consider that the electrodes surface is planar in the \( x, y \) plane. The 3D dielectrophoretic dynamic modeling simulator is designed to run on a classic \( PC \) with high performance (typically \( GHz \)) and it is not optimized to be integrated directly into a controller card with lower calculation performance (typically \( MHz \)). Thus, a simplification of the 3D simulator is proposed. We assume that the micro-bead will move only in a limited space above the electrodes surface in a parallelepipedic workspace. The simplified 3D DDM (SDDM) uses a similar approach to the 3D DDM presented above. In this SDDM, a database of the elementary spacial force is created. This database links the 3D dielectrophoretic force directly to the applied voltages, which will reduce sufficiently the computation time. Using the linear relationship between the electric field \( \overrightarrow{E} \) and the applied voltages \( U \), the dielectrophoretic force can be written as a second order equation with respect to the electric voltages. Using the electrodes configuration presented in the figure 5, and the following electric voltages vector:

\[
U = [u_1, u_2, u_3] = [V_1 - V_4, V_2 - V_4, V_3 - V_4],
\]

(9)

driving force \( [F_D_x, F_D_y, F_D_z] \) can be written as the following:

\[
F_D_x = f_{x1}u_1^2 + f_{x2}u_2^2 + f_{x3}u_3^2 + f_{x12}u_1u_2 + f_{x13}u_1u_3 + f_{x23}u_2u_3
\]

\[
F_D_y = f_{y1}u_1^2 + f_{y2}u_2^2 + f_{y3}u_3^2 + f_{y12}u_1u_2 + f_{y13}u_1u_3 + f_{y23}u_2u_3
\]

\[
F_D_z = -mg + f_{z1}u_1^2 + f_{z2}u_2^2 + f_{z3}u_3^2 + f_{z12}u_1u_2 + f_{z13}u_1u_3 + f_{z23}u_2u_3
\]

(10)

\( u_1, u_2 \) and \( u_3 \) are the varying voltages and \( f_{xij}, f_{yij} \) and \( f_{zij} \) are spacial functions in \( x, y \) and \( z \). Discrete values of these functions will be computed in a \( x, y \) and \( z \) grid points using the 3D simulator and stored in a database and a quadratic interpolation is used to evaluate these functions in an arbitrary \( (x, y, z) \) point inside the parallelepipedic workspace. Using this
Consequently, the computation time is reduced and few arithmetic iterations are executed in a very short time, even with the interpolation procedure. Indeed, 60 CPU clock cycles are needed to compute the 3 components of the dielectrophoretic force in a grid point, and 270 CPU clock cycle in an interpolated position. Thus if we consider that the micro-bead’s time response is $3\text{ms}$ and for a successful tracking 5 control sequence are generated, a controller card with 1MHz clock takes $0.2\text{ms}$ to compute the dielectrophoretic force using the SDDM.

B. 3D inverse dynamic model

The behavior of a micro-bead in a dielectrophoretic system is characterized by its high dynamics as presented above and the nonlinearity of the generated force with respect to the applied voltages as shown in the equation (11). The analytic inversion of the SDDM (11) is not possible due to the strong coupling between the control variables $u_1$, $u_2$ and $u_3$ and the generated force. One way to solve this problem is to use the Newton-Raphson numeric method which is able to find the values of the control variables with respect to a required value of the force. Newton-Raphson is a method for finding successively better approximations to the roots of a real-valued functions. By sampling the SDDM (11) and knowing the trajectory $[\hat{x}(t), \hat{y}(t), \hat{z}(t)]$ with respect to the time we are able to compute the appropriate control variable $U(t)$ using the Newton-Raphson method as illustrated in the figure 6:

![Fig. 5. Geometry of the electrodes and applied voltages: definition of control parameters $u_x$ and $u_y$.](image_url)

By sampling the dynamic equation (11) using a sampling period $T$ we obtain:

$$\begin{bmatrix} \hat{x}_{k+1} \\ \hat{y}_{k+1} \\ \hat{z}_{k+1} \end{bmatrix} = \frac{T}{6\pi\nu R} \begin{bmatrix} F_{D_x}(U_k) \\ F_{D_y}(U_k) \\ F_{D_z}(U_k) \end{bmatrix} + \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix}$$

where $\hat{x}_{k+1}$, $\hat{y}_{k+1}$ and $\hat{z}_{k+1}$ are the next trajectory point at the date $kT$. Applying the Newton-Raphson method to this model consists in finding iteratively a series of $u_1$, $u_2$ and $u_3$. At the date $kT$ we have:

$$U_{k+1} = U_k - J^{-1}(U_k) \begin{bmatrix} f_x(U_k) \\ f_y(U_k) \\ f_z(U_k) \end{bmatrix}$$

where $U_0$ are the last computed control variable, $J$ is the Jacobian matrix:

$$J = \begin{bmatrix} \frac{\partial f_x}{\partial u_1} & \frac{\partial f_x}{\partial u_2} & \frac{\partial f_x}{\partial u_3} \\ \frac{\partial f_y}{\partial u_1} & \frac{\partial f_y}{\partial u_2} & \frac{\partial f_y}{\partial u_3} \\ \frac{\partial f_z}{\partial u_1} & \frac{\partial f_z}{\partial u_2} & \frac{\partial f_z}{\partial u_3} \end{bmatrix}$$

and

$$f_x(U) = F_{D_x}(U) - 6\pi\nu R(\hat{x}_{k+1} - x_k)$$

$$f_y(U) = F_{D_y}(U) - 6\pi\nu R(\hat{y}_{k+1} - y_k)$$

$$f_z(U) = F_{D_z}(U) - 6\pi\nu R(\hat{z}_{k+1} - z_k)$$

The iterations classically stops when:

$$\|u_{1i+1} - u_1\| \leq \delta_u \quad \text{and} \quad \|u_{2i+1} - u_2\| \leq \delta_u \quad \text{and} \quad \|u_{3i+1} - u_3\| \leq \delta_u$$

where $\delta_u$ is an error threshold.

IV. EXPERIMENTATIONS AND RESULTS

A. Experimental set-up

In an experimental point of view, the main challenge is to build a control loop able to guarantee a high frequency calculation which requires to optimize the position measurement, the controller, the voltages generator. In micro-scale the most used position sensor is the camera. Thus using vision as feedback, the camera must be a high speed acquisition camera with a high speed communication protocol. As for the voltage generator, the digital analogical converter must have a very short latency (response time) controlled via also a fast communication protocol. These conditions direct us to a very limited choice. Among the different existing solutions we chose for the position sensor the "Photonfocus" camera with Camera Link communication protocol capable to acquire more than 1000 ips (images per second), in ROI mode (Region of Interest). The frame is grabbed using a PCI (Peripheral Component Interconnect) frame grabber, and the communication time in real time is less then $10\mu s$ also in ROI mode. As for the voltages generation we use the
Future works will be focused on the manipulation of smaller components dedicated to nanosystems.
voltages, but the reference trajectory is impossible to track. The controller computes the optimal trajectory (see video enclosed).

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