Modeling and control of non-contact micromanipulation based on dielectrophoresis.

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FEMTO-ST institute UMR CNRS 6174-UFC/ENSMM/UTBM
Automatic control and Micromechatronic System Department
24 rue Alain Savary, 25000 Besançon, France, EU

***Abstract*— Micro and nano-particles can be trapped by a non uniform electric field through the effect of the dielectrophoretic force. Dielectrophoresis (DEP) is used to separate, manipulate and sense micro particles in several domains, such as in biological or Carbon Nano-Tubes (CNTs) manipulations. This paper tackles the creation of a closed loop strategy in order to control, using DEP, the trajectory of micro objects using vision feedback. A modeling of the dielectrophoresis force is presented to illustrate the non linearity of the system and the high dynamics of the object under dielectrophoresis . A control strategy based on the generalized predictive control method is proposed with the aim of controlling the trajectory, taking advantage of the high dynamics despite the non linearity. Simulated results are shown to evaluate our control strategy.**

I. INTRODUCTION

Manufactured products become always smaller and integrate more and more functionalities in small volumes. Several applications fields are concerned such as bio-engineering, telecommunications or in a more general way Micro-Electro-Mechanical-Systems (MEMS). The assembly of these microproducts is a great challenge because of the microscopic sizes of the components. In fact, the major difficulties of micro-assembly come from the particularity of the micro-object's behaviours which are more function of the surface forces than the volumic forces [1], [2], [3]. The manipulation of a micro-object requires its handling, positioning, and release without disturbances of the surface forces such as electrostatic forces, van der Waals forces or capillary forces. The release is the more critical phase which is usually perturbed by adhesion phenomenon.

Several methods have been proposed in the last ten years to improve micromanipulations [4], [5]. The first approach deals with contact manipulation where the adhesion should be reduced or could be directly used for manipulation [6], [7], [8]. The release is the more critical phase which requires innovative methods to control and guarantee it despite adhesion. Dielectrophoresis force, which is the force applied on a polarizable particle in a non uniform electric field, has been recently used to induce repulsive force on micro-objects in order to release them [9]. The second approach consists in using non-contact manipulations like laser trapping [10] and non-contact dielectrophoresis [11]. These principles are not disturbed by adhesion but the blocking force remains low.

In this paper, modeling and closed loop strategy of DEP systems using vision feedback are proposed. By simulating the 3D behavior of micro particles under DEP force, in function of the electric potential applied on the electrodes and using the vision capture, the system is ready to include the feedback block. The problem which will be faced is the large difference between the high dynamics of the system (respond time $\simeq 1ms$) and the low speed rate of the vision capture ($\simeq 1$ image per 10 ms). We are a predictive control strategy based on the feedback of the vision sensor and a model of the DEP force.

II. MODEL PRESENTATION

A. Dynamic Model

The general expression of the dielectrophoretic force, created by a non uniform electric field, applied to a micro bead submerged in a liquid medium is [12], [13] is:

$$\overrightarrow{F_{DEP}} = 2\pi\epsilon_0\epsilon_p r^3 Re[K(\omega)]\overrightarrow{\nabla\mathbb{E}^2}. \tag{1}$$

$K(\omega)$ is the Clausius - Mossotti factor:

$$K(\omega) = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*}, \tag{2}$$

and

$$\epsilon^* = \epsilon + \frac{\sigma}{j\omega}, \tag{3}$$

where ϵ are the permittivities, σ are the conductivities, index *0* refers to the vacuum, index *m* refers to the medium and index *p* refers to the micro bead, r is the radius of the micro bead, ω is the angular frequency of the applied electric field, $\overrightarrow{\nabla}$ is the gradient operator and $\mathbb{E}$ is the root mean square magnitude of the sinusoidal electric field.

The electric field $\mathbb{E}$ is created by applying an electric voltages on pattern of electrodes as described in Fig. 1.

The dynamic model of the micro bead is defined by the Newton second's law. The force applied to the micro bead are the dielectrophoresis force, the Stokes drag force $\overrightarrow{F_{drag}}$ and its own weight $\overrightarrow{P}$ (see Fig.1).

If we consider that the position $X(x, y, z)$ of the micro bead is defined by its center's coordinates, thus the $\overrightarrow{\dot{X}}$ is the velocity of the particle and the $\overrightarrow{F_{drag}}$ verifies:

$$\overrightarrow{F_{drag}} = -6\pi\mu r\overrightarrow{V} = -k_\mu\overrightarrow{\dot{X}}, \tag{4}$$

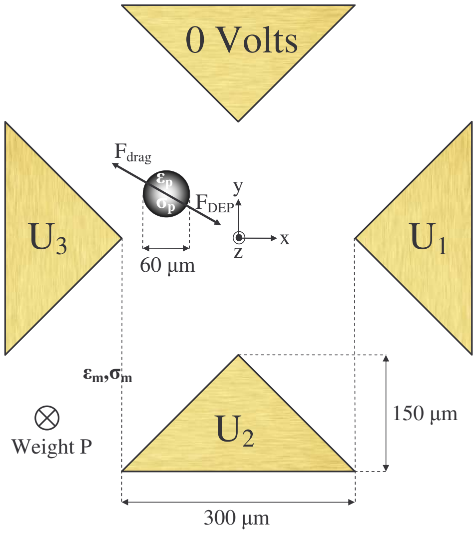

Fig. 1. DEP-based device used in this study

where μ is the dynamic viscosity of the liquid medium. Using Newton's second law the particle's motion is defined by:

$$\overrightarrow{F_{DEP}} + \overrightarrow{P} - k_\mu \overrightarrow{\dot{X}} = \mathcal{M}\overrightarrow{\ddot{X}} \tag{5}$$

where $\mathcal{M}$ is the mass of the micro bead and $\overrightarrow{\ddot{X}}$ is the acceleration vector. We have shown in [14] that, in this situation, the inertial term $\mathcal{M}\overrightarrow{\ddot{X}}$ is a negligible volumic effect in the micro-world : the respond time corresponding to the acceleration term is negligible compared to the respond time corresponding to the fluid dynamic term. Thus, the particle's motion equation can be reduced as follows:

$$\overrightarrow{\dot{X}} = \frac{(\overrightarrow{F_{DEP}} + \overrightarrow{P})}{k_\mu} \tag{6}$$

A voltage vector $U = [U_1, U_2, U_3]$ applied on the electrodes creates the non uniform electric field $\overrightarrow{E}$ which creates the dielectrophoresis force used to manipulate the micro particle. Equation (6) manages the dynamical behavior of the micro particle under dielectrophoresis force. More information on this model can be found in [14].

B. Study of the micro bead behavior

In order to present our control strategy, we are focusing on the electrode's geometry described in Fig.1 submerged in ultra pure water. We assume here that the micro bead only moves along the x axis, thus the position X of the micro bead is defined by $(x, y = 0, z = r)$. Projecting (6) along the x axis, the velocity of the micro bead is ruled by:

$$\dot{x} = \frac{F_{DEP}(x, U)}{k_\mu} \tag{7}$$

In order to maintain the micro bead's center along the x axis, and taking into consideration the electrodes symmetry, the control input vector, which is the applied voltage vector U, proposed here is:

$$U = [U_{ref} - \delta u, 0V, U_{ref} + \delta u]. \tag{8}$$

where U_{ref} is a fixed voltage, in this study it is equal to $75V$, and δu is the single control variable. The electric field and the applied voltage on the electrodes are linearly related, due to the electrostatic superposition principle and the proportional relation between the electric potential and the charge density:

$$\mathbb{E} = a(x)(U_{ref} - \delta u) + b(x)(U_{ref} + \delta u). \tag{9}$$

This relation allows to replace the electric field $\mathbb{E}$ in (1) by a linear combination of the applied voltages. Thus, from (7) the velocity $\dot{x}$ can be written as a second degree equation, coming from the electric field's square in the dielectrophoresis equation (1), with the respect to the control variable δu:

$$\dot{x} = f_1(\delta u) = \alpha(x)\delta u^2 + \beta(x)\delta u + \gamma(x) \tag{10}$$

where $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ characterize the dynamic model. They are function of the state variable x. The first problem to control this system is its non linearity which is shown in the equation (10). The first non linearity of the system with respect to the control variable δu is due to the square term δu^2. The second non linearity comes from the non linearity of the functions $\alpha(x)$, $\beta(x)$ and $\gamma(x)$. These functions characterize the system and they are identified using the hybrid simulation method, described in [14], which combines preprocessing FEM software simulated data and analytic equations.

Fig.2 shows the non linearity of these functions. In this figure, we clearly see that the functions $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ are not linear with respect to the state variable x. This non linearity increases as the distance between the micro bead and the electrode's edge decreases.

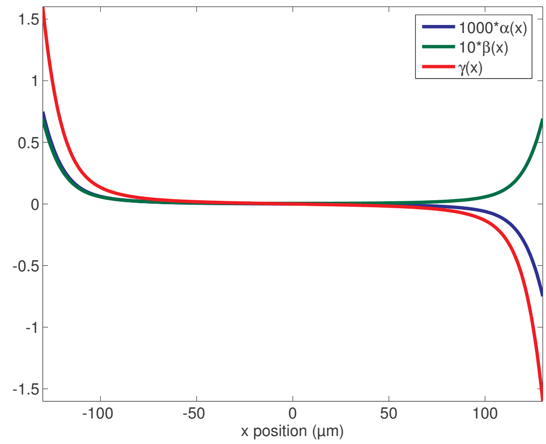

Fig. 2. The non linearity of the three functions $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ ($U_{ref} = 75V$) especially when $x \geq 50\mu m$, respectively expressed in $ms^{-1}V^{-2}$, $ms^{-1}V^{-1}$ and ms^{-1}.

Moreover, the micro bead reaches high speed motion when applying high voltages. Fig.3 shows the step response for a micro bead starting from the initial position $x_0 = 0\mu m$ and applying a voltage of $\delta u = 70V$, $60V$, $50V$ and $40V$. If we compare the time constant of the micro bead's response, which is close to $3ms$, to a relatively high speed camera of 400 ips (images per second) we can note that during this time only two positions can be measured.

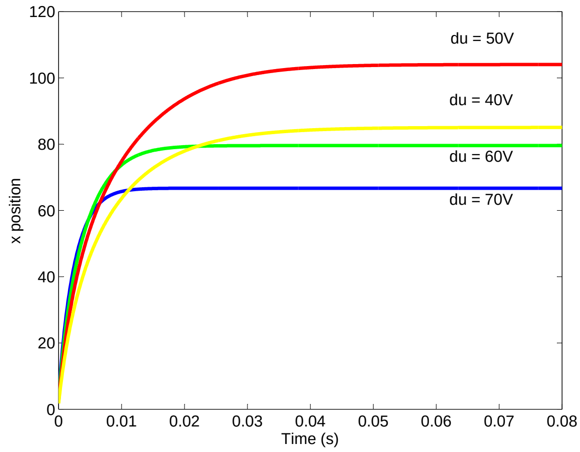

Fig. 3. Step response for a micro bead starting form $x_0 = 0\mu m$, $\delta u = 40V, 50V, 60V\ and\ 70V$ and $U_{ref} = 75V$

III. Control strategy

In order to control the micro bead's trajectory along a reference trajectory w in a dielectrophoresis-based device using vision feedback, two main difficulties occur. The first problem is the non linearity of the system with respect to the control variable δu as the equation (10) shows and the non linearity in relation to the state variable x due to the non linearity of the functions $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ as it is shown in Fig.2. Moreover, the other problem is the high dynamics of the system which induces high speed motion of the micro bead compared to the camera speed rate, which is one of the most conventional way to measure the micro bead's position. Both non linearity and high dynamics led us to develop an appropriate control strategy (Fig.4).

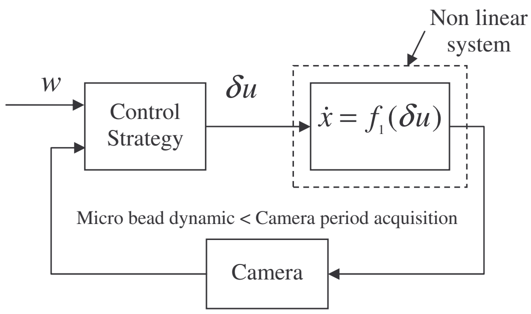

Fig. 4. Summary of the control strategy

A. Linear model

To resolve the non linearity problem, starting by the non linearity relative to the control variable δu, the first step consists of transforming this non linear system to another linear system relatively to a new control variable named ξ. Using the following variable transformation:

$$\xi = f_2(\delta u) = \left(\delta u + \frac{\beta(x)}{2\alpha(x)}\right)^2, \tag{11}$$

we are able to create a linear relation between the new control variable ξ and the velocity of the micro bead $\dot{x}$. The new linear dynamic equation is:

$$\dot{x} = \alpha(x)\xi + \rho(x), \tag{12}$$

where

$$\rho(x) = \gamma(x) - \frac{\beta^2(x)}{4\alpha(x)}. \tag{13}$$

Equation (12) solves the non linearity problem in relation to the new control variable ξ.

Concerning the non linearity in relation to the state variable, produced by the non linear functions $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ (see Fig.2), these functions can be estimated by using an estimated value of the state variable x. This estimated value is equal to the current position when it is available, and it is equal to the reference value w date when the state variable x is not available. This last case is based on the hypothesis that the reference trajectory is known at any time and the controlled position is relatively close to the desired position.

B. Generalized Predictive Control (GPC)

In order to control the high dynamics of the micro bead, a control strategy ables to apply a series of control variables while no position's informations are available between two successive camera acquisition is presented. One of the control strategy which fulfill these requests is the GPC. The goal of the generalized predictive control is to find the optimal future control actions that drive the future process output to track the reference trajectory as closely as possible in the presence of system constraints and disturbances [15]. The generalized predictive control is used in several domains of applications such as solar power plants [16], turbine engines [17] and robotic manipulators [18]. The main idea of the GPC is to find a future control sequence from a given time which minimizes the error between the predicted output and the reference.

Based on a numerical model, the GPC enables to calculate the optimal control sequence of N values ξ in the future which minimize the error between the output position and the reference w in N steps in the future.

The application of the GPC strategy on our system requires a discrete model. Considering that the camera acquisition period is T_c which means the position's information is updated each T_c seconds. During this period the controller calculates the appropriate control variable sequence of N values using the sample time T_s in order to track the reference trajectory with $N \times T_s \geq T_c$.

The details of the control strategy is presented in [19].

IV. Results and discussion

In order to test the proposed control strategy, the dielectrophoresis system described in Fig.1 has been simulated, where the liquid medium is ultra pure water with $\epsilon_m = 80\epsilon_0$, $\sigma_m = 10^{-16} Sm^{-1}$ and $\mu = 10^{-3} kg(sm)^{-1}$. The micro object is a silicium micro bead with radius $r = 30\mu m$, $\epsilon_p = 8.4\epsilon_0$ and $\sigma_p = 10^{-12} Sm^{-1}$. The frequency $2\pi\omega$ of the applied voltage used to create the non uniform electric field is $10kHZ$ and $U_{ref} = 75V$ and the applied voltage on the electrodes is limited to $U_{max} = 150V$. The sample time is chosen equal to $0.5ms$ and the camera has an acquisition sample time equal to $2.5ms$. Thus, the minimum value of the prediction's horizon N is equal to $2.5/0.5 = 5$ $steps$. In order to test the robustness of the control law, the model used in the GPC controller and the simulated model differs by adding errors of 20% on the electric permittivities of both medium and particle.

A. High dynamics

Firstly, the proposed control strategy has been tested on high dynamic reference trajectories. Considering a sinusoidal reference trajectory with period equal to 10 times the camera acquisition period, i.e. $25ms$ with a magnitude of $25\mu m$ around $x = 0$. In this range the model can be considered linear.

Fig.5 shows the output position of the the micro bead's calculated by the real system using the control variable δu obtained from the control variable ξ calculated by the proposed GPC applied on the model. This control strategy is also compared to a regular PI corrector to demonstrate the efficiency of our strategy. The proportional constant of this PI corrector is equal to the inverse of the gain of the system considered as a first order linear system in this range. The gain of the system is calculated and it is equal to $1.610^{-6}mV^{-1}$. The integrator constant of the PI corrector is equal to the time constant of the system which is equal to $3.610^{-3}s$.

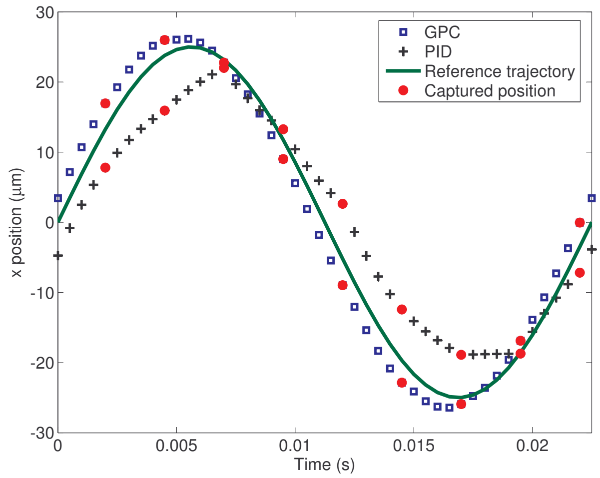

Fig. 5. Output trajectory of the system controlled by the generalized predictive control and compared to the PI control. The camera acquisition period is $2.5ms$

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B. Non linearity

Secondly, we test the proposed control strategy in the non linear range, by tracking a trajectory which reaches position near the electrode's edges. In this case the sinusoidal reference trajectory changes in magnitude and period. Fig.6 shows the output trajectory of the real system controlled by the proposed GPC strategy based on the model where the amplitude of the reference trajectory is $130\mu m$ and its period is $100ms$.

In this example, the micro bead goes toward the electrodes. At the time $t = 0.01s$, the micro bead's position is near to $x = 100\mu m$, the control did not find any value of the control variable ξ which nullify the error between the calculated and the reference position. The controller determines the optimum value which maximizes the velocity of the beads.

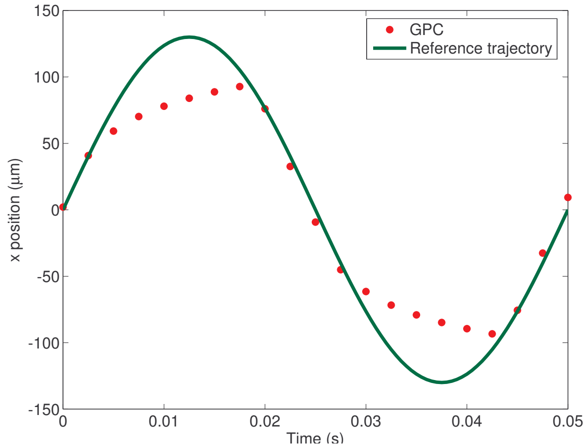

Fig. 6. Output trajectory of the Generalized predictive control tracking a long range reference trajectory using camera with acquisition period equal to $2.5ms$.

V. Conclusions

We have proposed a model and a closed loop control strategy based on the generalized predictive control of a dielectrophoretic-based device. The behavior of a micro bead, driven by dielectrophoresis force, is characterized by its high dynamics compared to the capture speed rate and the non linearity of its dynamic equation in relation to both the voltage variable and the position. The control strategy proposed provides the optimal sequence of voltage values with a smaller sampling rate then the camera speed rate. It enables to minimize the error between the micro bead's position and the reference even when the micro bead is near the electrodes where the non linearity is strong. The proposed control strategy is tested and compared to other regular control strategy such as the PI controller and several results are presented.

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