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Robust microscale grasping through a multimodel design: synthesis and real time implementation

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ABSTRACT

This paper deals with robust force control at the microscale for safe manipulation of deformable soft materials. Since mechanical properties of micrometer sized objects are highly uncertain, instability often occurs during a gripping task. This leads to object damage or destruction due to excessive gripping force. In this paper we propose the design of a robust dynamic output feedback controller that is able to insure desired performances for a set of 65 soft and resilient microspheres whose diameter ranges from 40 μm to 80 μm and stiffness varies from 2.8 N/m to 15.7 N/m. The degrees of freedom of the controller are managed by the use of a set of elementary observers. Robustness with respect to parametric uncertainties is satisfied thanks to an iterative procedure alternating between multimodel closed loop eigenstructure assignment and worst case analysis. The developed controller is of low order and can be implemented in real time. Robust gripping force control is for the first time demonstrated experimentally when dealing with the manipulation of a large number of variable deformable soft materials at the microscale. Both simulations and experimental results validate the interest of such control design approach.

1. Introduction

Microrobotics holds promises for the efficient and safe manipulation of biologic samples and living cells (Liu, Kim, Zhang, & Sun, 2009). In precursor works, techniques inspired from Atomic Force Microscopy have proven a reliable tool for the characterization of biomaterials. Muller, Helenius, Alsteens, and Dufrene (2009) used an AFM probe to obtain high resolution force images of living cells. Boukallel, Girot, and Régnier (2009) proposed an improved probe design to measure mechanical characteristics of cells in long traction/compression cycles. Desmaele, Boukallel, and Régnier (2012) introduced a dynamic measurement method improving the overall reliability. However, single cantilevers or similar designs are ill-adapted for manipulation. Recently, the development of dedicated microgrippers that include both actuation and force sensing in dimensions adapted to biologic samples opened the way to novel and cost-effective applications ranging from in vitro fertilization to genetics (Beyeler et al., 2007; Carrozza et al., 2000).

Biologic cells are highly deformable soft materials. They are very sensitive to applied force and to how they are handled. Consequently, the use of grippers for their manipulation calls for a precise force control of grasping. This particular issue is evidently not limited to biologic samples and is a general concern for micro- and nanoscale manipulation. To apply safe gripping forces required for the manipulation of soft objects, several solutions have been reported. Bolopion, Xie, Haliyo, and Régnier (2012) use haptic feedback allowing the user to interact with microscale objects and leaves the force control to the operator. In a more traditional approach, feedback control (Carrozza et al., 2000; Liu et al., 2009; Park et al., 2005) allows for an automated approach to gripping.

At the microscale, soft materials have mechanical properties, namely stiffness and damping, close to that of the actuation and sensing systems of microgrippers. Therefore, during gripping tasks, samples have enough variation to induce instabilities that damage the gripper or the sample. In the literature, microscale force feedback control designs are often based on PI, PID or LQG schemes

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(Boudaoud, Haddab, & Le Gorrec, 2013; Carrozza et al., 2000; Liu et al., 2009; Park et al., 2005). Controller synthesis is often achieved considering the mechanical properties of a single sample and closed loop performance is validated experimentally when gripping the sample used for the synthesis (Boudaoud et al., 2013; Liu et al., 2009). These approaches lack the robustness required for micromanipulation. To overcome this problem, H_∞ controllers proposed in Rakotondrabe, Haddab, and Lutz (2007) and Rakotondrabe and Le Gorrec (2010) are often used. Resulting schemes allow for a robust force control, but such controllers are often of high order and can be difficult to implement in real time due to the considered bandwidth (Boudaoud, Le Gorrec, Haddab, & Lutz, 2012; Poussot-Vassal et al., 2008).

The aim of the present work is to propose a robust control design procedure aiming at deriving efficient low order controllers. The synthesis is based on a closed loop eigenstructure assignment methodology as previously mentioned in Boudaoud et al. (2012). The shortcoming of this approach is that it cannot deal with uncertain and unmeasurable parameters. In gripping tasks, the size, the stiffness and the damping of the samples are part of uncertain parameters. To overcome this issue, based on a set of elementary observers, multi-model assignment constraints are defined using an iterative procedure (Magni, Le Gorrec, & Chiappa, 1998). The most relevant multimodel constraints are defined considering parametric uncertainties in a set of 65 soft and resilient microspheres with diameters ranging from 40 μm to 80 μm and stiffness from 2.8 N/m to 15.7 N/m. The order of the controller is equal to the number of observers and is potentially low.

The proposed approach is designed considering an electrostatic microgripper with an integrated force sensor and the set of microspheres with varying size and stiffness. For control purposes, a non-linear coupled model of the microgripper with an object is established. The non-linear model is formulated in Section 3 into an uncertain Linear Time Invariant (LTI) model taking into account the dynamics of the actuator, the force sensor and the gripped microsphere. Gripping force control is then achieved in Section 4 through the above mentioned methodology. Results presented in Section 6 show the first experimental demonstration of robust gripping force control at the microscale for the manipulation of a large number of soft materials with varying mechanical properties. In Section 7, the applicable range of the control design for microscale objects grasping is discussed.

2. Specifications of the microgripper and sample microspheres

The microgripper used in this study is Fem (2009). The first version of this microgripper was described in Beyeler et al. (2007). A detailed description of its architecture and working principle can be found in Boudaoud et al. (2013). This two-finger (arms) microgripper depicted in Fig. 1 includes comb-drive actuation on one part and capacitive force sensing on the other. The gap of the gripper is 100 μm.

Manipulated samples are thermoplastic particles called expancel microspheres. Expancel are thermoplastic microspheres enclosing hydrocarbon. These microspheres expand when heated, producing many applications. They are deformable, soft and resilient, with properties close to that of biological samples (Kemper, 2004) which makes them very attractive for force control experiments at the microscale. Three kinds of microspheres have been used in this study: model 1, model 2 and model 3 (Table 1). For each model, the manufacturer provides the size, with uncertainties of about 10% as shown in Table 1, but the stiffness and the damping are not known. Hence, the size and both the stiffness and the damping of a set of 65 microspheres are experimentally identified in Section 3.2 using the microgripper.

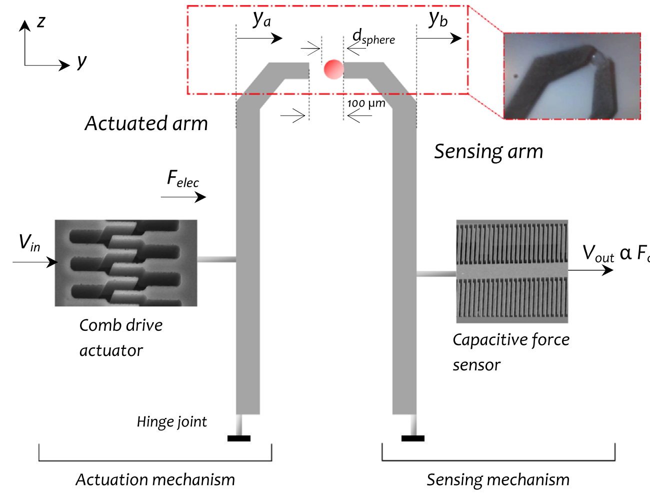

Fig. 1. Simplified scheme of the microgripper.

Table 1
Reference, diameter and number of characterized Expancel microspheres.

Model	Reference	Diameter	Number of samples
Model 1	Akz1 (2011)	57 μm ± 14 μm	25
Model 2	Akz2 (2011)	55 μm ± 5 μm	17
Model 3	Akz3 (2011)	68 μm ± 10 μm	23

3. Non-linear modeling of the grasping

3.1. Modeling of the gripper

In Boudaoud et al. (2012), a non-linear model of the actuation mechanism (Fig. 1) is described along with an experimental validation. It is a mass–spring–damper model where the stiffness (k_a) and the damping (d_a) are non-linear polynomial functions of the position of the actuated arm y_a:

$$k_a(y_a) = \sum_{i=1}^{6} k_{ia} y_a^{i-1} \tag{1}$$

$$d_a(y_a) = \sum_{i=1}^{4} d_{ia} y_a^{i} \tag{2}$$

k_{ia} and d_{ia} are constant coefficients of the stiffness and the damping polynomial functions respectively.

This mass–spring–damper model is extended to the case where a microsphere is gripped between the actuated and sensing arms. The model of the overall system is obtained by coupling both the non-linear model of the actuation mechanism with a linear mass–spring–damper model of the sensing mechanism and considering the gripped object as a spring–damper with a stiffness k_o and a damping d_o. It leads to the following model:

$$\begin{bmatrix} \dot{y}_a \\ \ddot{y}_a \\ \dot{y}_b \\ \ddot{y}_b \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_o + k_a(y_a)}{m_a} & -\frac{d_o + d_a(y_a)}{m_a} & \frac{k_o}{m_a} & \frac{d_o}{m_a} \\ 0 & 0 & 0 & 1 \\ \frac{k_o}{m_b} & \frac{d_o}{m_b} & -\frac{k_o + k_b}{m_b} & -\frac{d_o + d_b}{m_b} \end{bmatrix} \begin{bmatrix} y_a \\ \dot{y}_a \\ y_b \\ \dot{y}_b \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{N_a \varepsilon h_z}{2 m_a g D_a} \\ 0 \\ 0 \end{bmatrix} V_{in}^2$$