Extended High-Gain Observer for Robust Position Control of a Micro-gripper in Air and Vacuum

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Abstract—**This paper aims to develop a position tracking controller for a micro-gripper's tip. The controller should be robust, able to compensate external disturbances and perform precise reference tracking under parameter variation and incertitudes. It becomes clear when considering the gripper's response on two different environments: air and vacuum. In this work, two models were identified based on experimental data, one for each case of study, and an extended high-gain observer controller based on output feedback is proposed. Simulations show that the controller, chosen to achieve a desired performance for the system in air, is able to maintain similar results in vacuum. The proposed setup was implemented in real-time for the system in air and simulated for vacuum.**

I. INTRODUCTION

In micro-manipulation task, high positioning accuracy is desired for handling, characterizing and displacing samples. However, when performing tasks at very small scale, certain problems arise. Micro-electromechanical systems have, due to imperfections in the fabrication process, incertitudes that are an important factor which limits the performance of manipulation tasks. Moreover, non-linearities and non-modelled dynamics can also have an important effect, degrading the system's performance or even destabilizing the closed loop. Sometimes, the characterization itself can become a complex task. This is the case of dynamic characterization in vacuum environments.

The dynamic characterization of devices in vacuum involve a more elaborated experimental setup from the practical point of view, where special components are often required and the vacuum chamber volume limits the available working space. It is known that the behaviour of components, such as cantilevers, is largely affected by pressure changes [1], [2], altering its vibration modes and, more importantly, the damping of the system. The development of a control law robust to these parametric variations, capable of good response and disturbance rejection characteristics, is a challenge. The development of such controller would be of great practical interest, simplifying the use of instruments such as the SEM for micro and nano-scale manipulation [3].

To achieve this objective, robust controllers are essential. One example is the H_∞ controller ([4], [5], [6]), where weighting functions are used to improve the system's robustness and to attenuate disturbances. This approach often requires a relative precise knowledge of the system and may require a case-by-case study, what can be resource and time consuming. Another possibility is the use of active disturbance rejection controllers (ADRC), a different class of controllers which can deliver fast tracking of references with disturbance compensation [7]. Examples of active disturbance compensators for micro-grippers can be seen in [8], [9]. However, most of the existing disturbance estimators rely on accurate modelling of the plant [10]. This is the advantage of the Extended State Observer (ESO), a ADRC method that aims to minimize model dependency.

This paper proposes the use of an ESO to perform output feedback control over a commercially available micro-gripper. The ESO, proposed in 1995, is used to estimate the states and uncertainties/disturbances acting over the system, compensating them in real-time [11], [12]. If the observer's dynamic is sufficiently fast, the estimated states and uncertainties can be used in the feedback control to recover state feedback performance. For this purpose, the gains of the ESO are choosen accordingly based on the high-gain method [13]. This results in robust the closed loop system's performance in face of uncertainties, parameter variation and disturbances, reducing its dependency over accurate models.

This work is separated in four parts. Section II describes the identification and validation of a micro-gripper actuation finger in two environments of interest: air and vacuum. Section III develops the extended high-gain observer control, defining the control parameters to be adjusted. Section IV presents the results, where the gripper's models for air and vacuum in closed loop are simulated, and the model for closed loop in air is implemented in real-time. Finally, Section V summarizes the most important points of this work and proposes ideas for further developments.

II. EXPERIMENTAL IDENTIFICATION OF A MICRO-GRIPPER FINGER'S

A commercially available micro-gripper (FTG-30, from FemtoTools GmbH.) was used for this work. The micro-gripper consist of two fingers: one, actuated by a comb-drive mechanism, and a second passive finger, capable of force measurement through a built-in capacitive sensor. Figure 1 shows the gripper and its components. This work will focus on the actuated finger of the gripper during the free movement (no contact interaction with samples or the sensor finger). The actuated finger's dimensions are approximately 4000x120x50 μm^3, and the nominal distance between its fingers is $30\mu m$, defining its working range.

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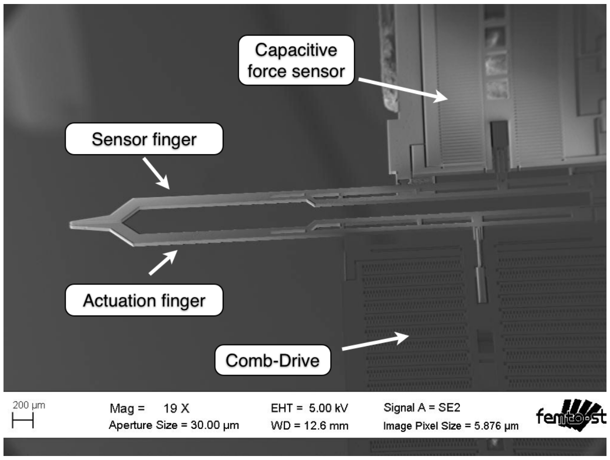

Figure 1: View of the micro-gripper, indicating its components.

A. *Micro-gripper's identification in air*

To obtain the micro-gripper's dynamic model, a vibrometer (SIOS SP-120) was used to measure displacements at the gripper's tip. The vibrometer is capable of precise (resolution of a few nanometers) and fast (sampling frequency up to hundreds of Khz) data acquisition. The signals applied to the gripper were generated by a DSpace card, and amplified using a Krohn-Hite 7602M power amplifier. Small steps of voltage ($\Delta V = 0.5$ Volts) were applied for different operation points ($V = [5...60]$ Volts). This data was used to obtain a set of linear models around different operation points. The gripper's response was approximated by a second order system:

$$M_i\ddot{x} + C_i\dot{x} + K_i x = G_i K_{elec} V_{in}^2 \qquad (1)$$

where M represents the mass, C the damping, K the stiffness, K_{elec} electrostatic gain of the comb drive actuator and G_i an input gain (ideally $G_i = 1$) for each one of the i models. The electrostatic gain K_{elec} can be estimated using the equation:

$$K_{elec} = \frac{N_a.\xi.h_z}{2.g} \qquad (2)$$

with N_a the total number of fingers in the comb-drive, ξ the permissivity of the dielectric material, h_z the thickness of the comb-drive fingers and g the gap between two fingers [14].

Parameters were found for each of the operation points through system identification techniques. Considering the same value of M_i for all models, it was possible to identify that certain parameters presented a large variation in the studied range (stiffness K and input gain G), while the damping C remained almost unchanged for all range, therefore being considered the same for all models.

Figure 2 shows the relation between the parameters K_i, G_i and the operation point $V_{in} = V + \Delta V$. The variation in the parameters is relatively small for low voltages ($V_{in} < 30$, corresponding to a tip displacement range of approximately $5.5\mu m$ at steady state), and becomes more important at the high end of the gripper's operation range. From the experimental data, up to 30% variation in the input gain G_i and more than 25% of variation in the stiffness K_i were observed. The stiffness variation produces a shift on the first vibration mode of the system, ranging from $1040Hz$ to 1180 Hz. This characterization step shows how important parameter variation can be and reinforce the importance of robust control laws capable of dealing with variations and uncertainties in models.

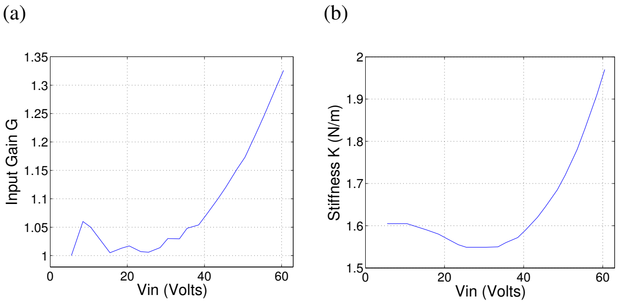

Figure 2: Variation of model parameters for different input voltages V. a) Input gain G. b) Stiffness K.

To obtain a single model capable of representing the behaviour of the gripper's actuated finger in all the working range, the parameters K_i and C_i were substituted by polynomial functions of the input tension $K(V_{in})$ and $G(V_{in})$. The coefficient of the polynomials were chosen to best fit the curves given in Figure 2 between 25 and 60 V, corresponding to a tip displacements range between 5 and 27 μm. To validate this approach, the obtained system was compared with experimental data for large steps of V_{in}. The results show good agreement between simulation and experimental data, with a first mode frequency estimation error of less than 2 Hz and a steady state displacement error lower than 0.05 μm. Figure 3 shows a comparison between experimental and simulated models for a large input voltage step. This general model is therefore able to represent dynamics of the real system, and will be used as test bed for the controllers.

B. *Micro-gripper's identification in vacuum*

A similar identification process was applied to the gripper in the vacuum. In this experiment, both gripper and vibrometer were placed inside the vacuum chamber of a scanning electron microscope (SEM) in a dedicated setup. The gripper model was also selected as in the previous step (Equation 1, and the parameters were identified. The gripper's mass in both environments was considered the same.

Figure 4 compares the step response of the gripper to an input step signal between air and vacuum. It is clear that damping in vacuum is smaller, due to the lack of fluid drag force. Through the parametric identification, a small increase in the stiffness value was also observed. The variation of stiffness for different operation positions in vacuum shows a similar tendency as seen in air, with a small increment offset. The gain input G could not be precisely determined, and the

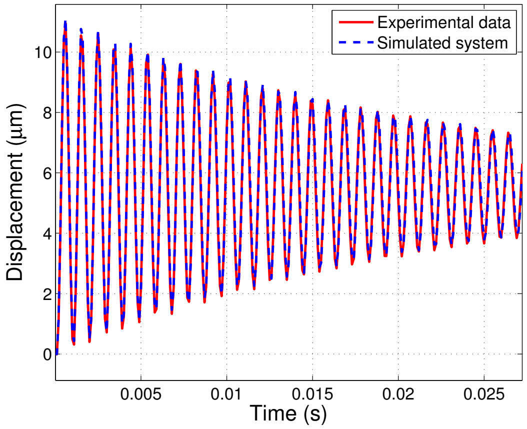

Figure 3: Comparison between experimental data and simulation of the obtained system for large displacements (30 Volts step).

values of the air estimation were used. Using the obtained parameters, the estimated vacuum model was then validated. Comparing simulation and experimental data for large steps of V_{in}, a good agreement in the first mode frequency and damping characteristics was found, with peak frequency error lower than 6 Hz and steady state displacement error lower than 0.2 μm.

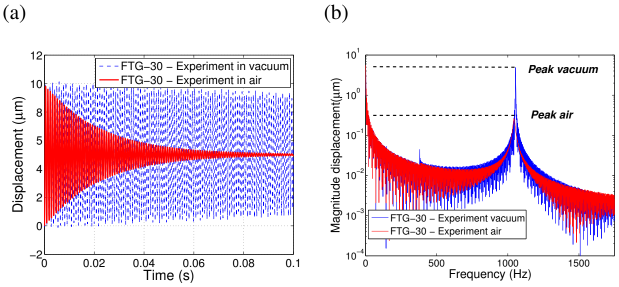

Figure 4: Step responses of the micro-gripper in air and vacuum in (a) time and (b) frequency. The dotted line serves as eye guide for the first mode peaks amplitudes.

Table I resumes the estimated parameter values for both cases, air and vacuum. The large damping variation between air and vacuum, together with the parametric variations of stiffness K and input gain G, present an important challenge to overcome.

Table I: Parameters for the micro gripper in different environments. *The parameter could not be precisely determined, values obtained in air were used.

	M	K	C	G
Air	$3.6e^{-8}$	$[1.55, 1.97]$	$3.2e^{-6}$	$[1, 1.33]$
Vacuum	$3.6e^{-8}$	$[1.63, 2.03]$	$2.5e^{-8}$	$[1, 1.33]^*$

III. EXTENDED HIGH GAIN OBSERVER CONTROL

The objective is to obtain a controller capable of tracking a reference position set-point in all the range of operation, in both environments (air and vacuum). As seen before, the range of parametric variation where the system can operate is meaningful. A common approach would be the development of a robust H_∞. However, this technique depends on the choice of weighting functions, generally resulting in high-order controllers, and requiring an *a priori* knowledge of the parametric variation. Another option is the use of extended disturbance observers, where all the unknown disturbances and parameters are clustered together in a single term, that is estimated by the observer and can be then compensated by the controller. In this paper, a special case of disturbance observers was chosen: the output feedback extended high-gain observer, due to its robustness to parametric variation, relatively low order and easy implementation.

This controller synthesis is performed in two parts. First a state feedback controller is designed to achieve a desired performance and ensure asymptotically stability, followed by the design of an extended high-gain observer, with a fast enough response to recover the performance of the state feedback system. A more complete explanation of this family of controllers can be seen in [15], [12]. Here a simplified synthesis is presented. Given a system in the form:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= b(x,d) + a(x)u \\ y &= x_1 \end{aligned} \tag{3}$$

with $b(x,d)$, $a(x)$ functions of the states x and a d unknown input disturbance. For the models obtained in the previous section, $b(x,d) = -(K/M)x_1 - (C/M)x_2 + d$, $a(x) = (GK_{elec})/M$ and $u = V_{in}^2$. The variables are then renamed as $K_e = K/M$, $C_e = C/M$ and $F_e = a(x)$.

The control objective is to track a reference position signal r. The tracking error, defined by $e_1 = x_1 - r$, has its dynamics described as:

$$\begin{aligned} \dot{e}_1 &= \dot{x}_1 - \dot{r} = e_2 \\ \dot{e}_2 &= -K_e(e_1 + r) - C_e(e_2 + \dot{r}) - \ddot{r} + d + F_e u \\ y &= e_1 \end{aligned} \tag{4}$$

Supposing that all the states of the system are available, a state feedback controller $u = -\Phi e = -[\phi_1 \quad \phi_2]e$ can be implemented to stabilize around the system the origin $e = 0$. The closed loop form for system (4) is then given by:

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= -e_1(K_e + F_e\phi_1) - e_2(C_e + F_e\phi_2) + w(r,\dot{r},\ddot{r},d) \end{aligned} \tag{5}$$

with $w(r,\dot{r},\ddot{r},d) = -K_e r - C_e\dot{r} - \ddot{r} + d$. The origin of the system without input ($w = 0$) should be made asymptotically stable. It is possible to choose values for ϕ_1, ϕ_2 to ensure that.

To be able to implement the controller, the states should be estimated using only the measured output y. If the estimation dynamic is sufficiently faster than the system's dynamics, and the estimation error approaches zero, it is possible to obtain a performance similar to the system with state feedback. From Equation 4, the variables a and b for this form are defined as:

$$\begin{aligned}\dot e_1 &= \dot x_1 - \dot r = e_2\\ \dot e_2 &= \underbrace{-K_e(e_1 + r) - C_e(e_2 + \dot r) - \ddot r + d}_{b(e,r,\dot r,\ddot r,d)} + \underbrace{F_e}_{a} u\end{aligned} \tag{6}$$

where $a \neq 0$.

These variables represent the unknown real values of the system. Considering $b_0(e)$ and a_0 the nominal values of these parameters, and σ the difference between them and the real values,

$$\sigma = b(e, r, \dot r, \ddot r, d) - b_0(e) + (a - a_0)u \tag{7}$$

it is possible to extend the dimension of the system 6 by adding σ as a state variable.

$$\begin{aligned}\dot e_1 &= e_2\\ \dot e_2 &= \sigma + b_0(e) + a_0 u\\ \dot\sigma &= \varphi(e, u, \dot u, r, \dot r, \ddot r, \dddot r, d, \dot d)\\ y &= e_1\end{aligned} \tag{8}$$

Assuming $\dot\sigma$ bounded over the domain, the observer for the above system would take the form:

$$\begin{aligned}\dot{\hat e}_1 &= \hat e_2 + h_1(y - \hat e_1)\\ \dot{\hat e}_2 &= \hat\sigma + b_0(\hat e) + a_0 u + h_2(y - \hat e_1)\\ \dot{\hat\sigma} &= h_3(y - \hat e_1)\end{aligned} \tag{9}$$

Computing the estimation error $e - \hat e$ and it derivative (using Equations 8 and 9), it is possible to show that, choosing large values for h_i, the influence of σ in the estimation error can be made small. A particular form of this observer, through the use of high-gains, is given by selecting h as:

$$h_i = \frac{\alpha_i}{\epsilon^i}, \tag{10}$$

with $\epsilon \ll 1$ and α_i positive constants such that the polynomial $s^3 + \alpha_1 s^2 + \alpha_2 s + \alpha_3$ is Hurwitz. The choice of a small value for ϵ, or similarly high values of h_i produces the high gains that name this method.

Taking the final controller as a feedback linearisation in the form

$$u = \frac{1}{a_0}\left(-\hat\sigma - b_0(\hat e) + \Phi\hat e\right) \tag{11}$$

the uncertainties and disturbances, estimated by $\hat\sigma$, are compensated by the control if the observer dynamics is selected to be fast enough. To avoid the peaking phenomenon [16] (effect that occurs when a sufficiently high gain of the observer produces an impulsive-like behaviour), the control signal u should be saturated, i.e. limiting its value to the operation range of the micro-gripper.

IV. RESULTS

Firstly, closed loop system with the general model described in Section II and the proposed observer and controller were simulated. As the model input is a function of V_{in}^2, the variable change $U = V_{in}^2$ was made in the controller synthesis to render the input linear. The reference was selected as a set of steps of different amplitudes, combined with a low pass pre-filter $F_{ref} = \beta/(s + \beta)$. The filter was selected to ensure a sufficiently smooth reference signal. In this step, a compromise should be found between the reference filter value β, the observer gains α and ϵ, and the controller gain Φ.

The value $\beta = 70$ was selected so that the settling time response would be smaller than 0.1 second (similar to the open loop response in air) without overshoot, although faster filters can be used. The controller parameter Φ was selected as $[-1;\ -10000]$, and the observer's parameters were chosen as $\alpha_1 = 3$, $\alpha_2 = 3$, $\alpha_3 = 1$ and $\epsilon = 5e^{-4}$. The numerical values were found iteratively by testing their effects in the simulation (following the conditions imposed in Section III) to obtain a good performance for the gripper's model in air, i.e. obtain a response with reduced oscillations can be accomplished by choosing a large value for ϕ_2.

The simulation result for the micro-gripper in air is shown in Figure 5. The tracking error converges to zero in steady state, and the controller is stable in all the working range. In the detail, it is possible to notice during transient phase a small difference between reference and position. By selecting a faster observer (i.e. decreasing the value of ϵ), it would be possible to reduce the tracking error in the transient period.

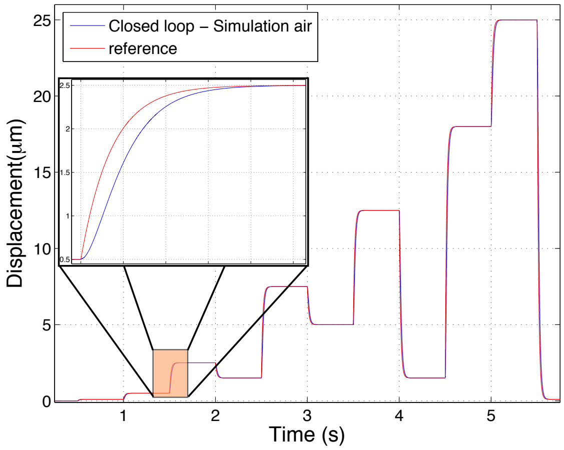

Figure 5: Simulation result for the proposed closed loop system in air.

One of the most important aspects of the high-gain observer is its robustness do disturbances and parameter uncertainties. Figure 6 shows the estimation error $\hat x_1 = x_1 - r$ andthe value of $\hat\sigma$ for an applied input disturbance to the system $d = 0.2 + 0.1sin(100\pi)$ starting at $t = 0.2$. Two different values of ϵ were considered: $5e^{-4}$ and $2e^{-4}$. From the curves, it is possible to see that the error due to the sinusoidal disturbance is further reduced for smaller values of ϵ, as the estimation of σ converges faster to its true value.

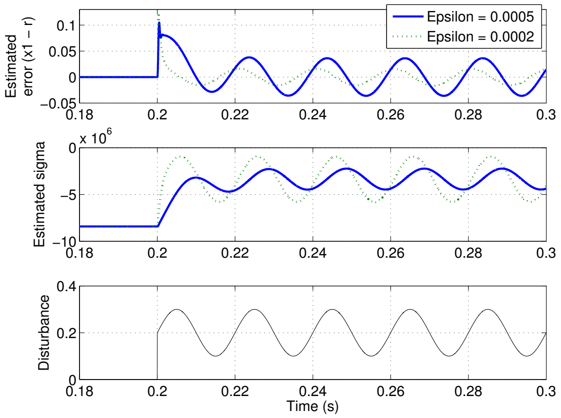

Figure 6: Observer estimation of $\hat{x}$ and $\hat{\sigma}$ for the closed loop system in air under a disturbance d, for different values of ϵ.

The above controller was implemented in real time to validate the approach. A set of steps of different amplitudes was applied to the system, and results are presented in Figure 7. The system was stable in all tested range (displacement of the tip between 0.1 and 25 μm), with a RMS error smaller than 0.012 μm around the reference for all operation range. The detail in the graph shows the effects of measurement noise in the system. Similarly to the simulation, there is a small difference in the transient tracking phase. Also, a small inverse response during reference changes was notices. This is attributed to the real time implementation, that introduces the use of sampled data and a small time-delay. It is known that, under a sufficiently small sampling period T, the properties of the observer (i.e. stabilization and performance) will be recovered in the discrete implementation [13]. Modifying the simulation to account for these effects, through the use of zero-order holders and delays, shown a similar performance degradation and inverse-response after reference changes as in the experiment.

These undesired effects can be reduced by choosing smaller value for ϵ and T. However, due to hardware limitations and delay imposed for the experimental setup, its value are limited in practice. This bounds its convergence speed and, consequently, its tracking and disturbance rejection performances. The measurement noise, an critical element for high-gain observers, did not pose a problem for this experiment, as the selected gain was not large in relation to the existing measurement noise level.

A last set of simulations was made to verify if the same controller would be able to stabilize and deliver a similar performance to the modelled micro-gripper system in vacuum. The parameters of the gripper were changed (Table I), although the same controller and observer were used. The achieved response for the system was similar to the air response, where the observer was able to estimate the parameter variation. A simulation was performed, where the effects of sampling and time delay were added. Figure 8 shows the result, where the tracking is achieved with a similar performance results as the system in air. It is important to notice that, even though the sampled system presents a small degradation for the chosen parameters, it is still robust throughout the range, correctly tracking the reference.

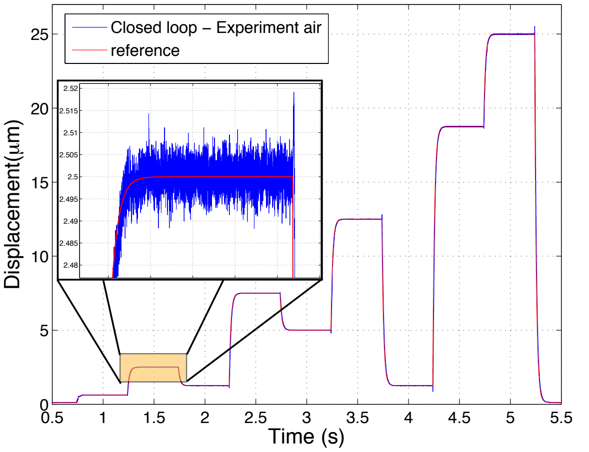

Figure 7: Experimental result of the closed loop system in air, detailing the influence of measurement noise.

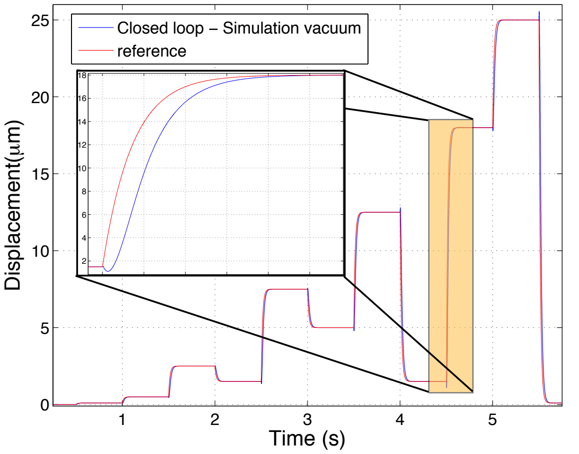

Figure 8: Simulation result of the closed loop system in vacuum, considering sampled signals and delay introduced by the hardware.

The influence of disturbance in the system was also analysed. An input disturbance $d = 0.2 + 0.1sin(100\pi)$ was applied to the system. Figure 9 shows a comparison of estimation error $\hat{e}$ and $\hat{\sigma}$ for air and vacuum. The overall behaviour of both systems for the same controller is very similar, keeping the tracking close to the desired position and rejecting the disturbance step. It is possible to see in $\hat{\sigma}$ a difference in the estimation of both parameters, which is expected, as it estimates the sum of disturbance and parameter's difference from the nominal values.

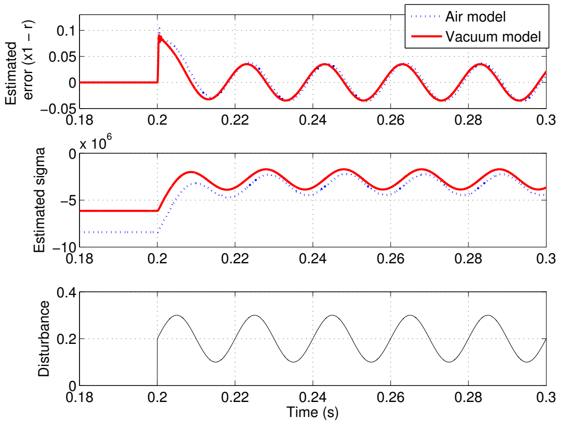

Figure 9: Simulation result of the closed loop system in vacuum, considering sampled signals and delay introduced by the hardware.

V. CONCLUSION AND PERSPECTIVES

This work described an output feedback controller based on an extended high-gain observer for the actuated finger of a commercial micro-gripper. The observer is used to estimate the states of the system and its uncertainties and disturbances from position measurements of the actuated finger acquired with a vibrometer. The objective was to obtain a simple to implement controller that is robust enough to overcome the parametric variation of the gripper when operating in two different environments: air and vacuum. Two models were obtained and validated from experimental data, one for each environment. In addition, each model contained variable stiffness and input gain. A synthesis of the method for obtaining the controller was shown and the closed loop system was simulated for the different working conditions. The results show that, given an adequate selection of control parameters, the system's response for both sets of estimated micro-gripper parameters (air and vacuum) remains stable throughout the range, correctly tracking position references. Furthermore, this extended observer can estimate non-static input disturbances and reduce their effects. This can facilitate micro-manipulation task, reducing the necessity of dynamic identification and calibration of actuators and the dependency of accurate model identification.

An important factor to consider is the limitation imposed by practical implementation constraints. In this case, the sampling period and delays introduced for the real-time control reduced the achieved performance, as the value of ϵ can not be made arbitrary small. Possible solutions for this include a discrete implementation of the extended observer to take in consideration these behaviours, or the direct measurement of the vibrometer's analog output signal to reduce the introduced-delay.

Future work include the experimental validation in vacuum, of the proposed control law and improvements in the overall performance, by developing a discrete extended high gain observer to overcome some of the limitations imposed by the hardware. Also, the extension of the system to include both the grippers fingers, and use the whole model in manipulation tasks, where the observer could be used to compensate the interaction forces and uncertainties in samples characteristics.

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