Closed-Loop Tracking of Large Displacements in Electro-Thermally Actuated VO₂-Based MEMS

Emmanuelle Merced, Student Member, IEEE, Xiaobo Tan, Senior Member, IEEE, and Nelson Sepúlveda, Senior Member, IEEE

Abstract—The large displacements produced by vanadium dioxide (VO₂) integrated microelectromechanical systems (MEMS)-based actuators have been precisely controlled through the use of a simple proportional-integral-derivative (PID) controller and an integrated heater. A complete device characterization is performed, including quasi-static response, frequency response, creep, repeatability, and rate dependency. These characterization results are used to design, simulate, and implement two PID controllers for closed-loop device actuation optimized for different control specifications. To validate the performance of the designed controllers, step and sinusoidal reference tracking experiments are performed. Highly accurate deflection control is observed for each case with a displacement range of 80 μm. Zero average steady-state error and fast actuation, up to 0.34 ms, are observed for the step reference tracking experiment with some signal oscillations resulting from the limit cycles produced by the VO₂ hysteresis. The root-mean-square error obtained for the sinusoidal reference tracking was found to increase for increasing frequencies due to the phase lag. A comparison between open- and closed-loop control is also performed, which shows the far superior stability and performance of the latter when the sample temperature is varied. The obtained results show that the VO₂-based MEMS actuators, although characterized by a complicated hysteretic and nonmonotonic deflection-to-heater current behavior, can be accurately controlled with a simple PID controller.

Index Terms—Vanadium dioxide, MEMS, micro actuator, closed-loop control, phase transition.

I. INTRODUCTION

IN RECENT years, there have been many efforts to incorporate vanadium dioxide (VO₂) as the “active” element in micro-actuators due to its abrupt (full actuation occurs within ~10 °C) [1] and reversible structural transition, which produces high energy densities [2] and large displacements [1], [3]. Through the successful integration of heaters in the fabrication of these actuators, research groups have improved electro-thermal bimorph technologies by decreasing power consumption and response times; and increasing operational ranges, using the electro-thermally driven transition [4]–[6].

Nonetheless, the high sensitivity of VO₂-based actuators to temperature fluctuations represents a major challenge when implementing such devices in actual applications with non-controlled environments. The work presented here shows the first closed-loop control of electro-thermally actuated VO₂-MEMS-based devices using a PID controller.

VO₂ is a solid-to-solid phase transition material first reported by Morin in 1959 [7]. During this reversible transition, the electrical [7], mechanical [1] and optical [8] properties of the material change abruptly, which has been exploited in numerous applications ranging from micro-actuation [2], [3] to mechanical and optical memories [5], [9], [10]. Although the mechanism driving the mechanical transition in VO₂ is still subject of debate, it has been strongly related to a Peierls transition; during which the crystallographic plane of the VO₂ parallel to the substrate shrinks [11] producing a high compressive stress capable of bending micro-structures.

The rest of this document is organized as follows. Section II details the device design and fabrication as well as the measurement setup used for device characterization and control. A complete device characterization is presented in Section III, which covers quasi-static analysis, frequency response, time response, reliability, and rate dependency. In Section IV, the dynamic model for the micro-actuator is derived, which includes electro-thermal and mechanical effects, and then, the model is used to design two PID controllers with different control specifications. The PID controllers are then implemented and tested under step and sinusoidal reference tracking experiments. The results are discussed in Section V along with a comparison between open-loop and closed-loop control.

II. EXPERIMENTAL PROCEDURES

A. Device Fabrication

The micro-actuator used in this work consisted of a silicon dioxide (SiO₂) micro-cantilever with a platinum (Pt)/titanium (Ti) pattern inside the structure and was developed following a simple two mask fabrication process flow, which is shown in Fig. 1. The Pt/Ti layer was used as the device heater (8 μm wide and 5 μm from the cantilever structure sidewall) and also for creating electrical contacts to the VO₂ (18 μm wide) for characterization purposes. The process started by depositing a 1 μm layer of SiO₂ using low thermal oxide (LTO) deposition on a silicon (Si) wafer 500 μm thick. A Pt (150 nm)/Ti (50 nm) layer was deposited through evaporation and patterned with lift-off to form the heating element.

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and the VO₂ resistance contacts. The separation between the electrode used for measuring the resistance of the VO₂ and the heater was 3 μm along the cantilever. A second SiO₂ layer 1 μm was deposited to protect the Pt heater and isolate it from the VO₂ deposited in the last step. A lithography process was then performed in order to define the geometry of the structure and expose the Si substrate for etching. In addition, two sets of squares were etched in order to create electrical contacts from the Pt to the VO₂. For releasing the structure, the SiO₂ was used as a hard mask in order to isotropically etch the Si using XeF₂. The finalized structure is 548 μm long, 48 μm wide, and 2 μm thick.

After fabrication, the actuator was coated with a 200 nm thick VO₂ film using pulsed laser deposition. A shadow mask was used to cover the electrode pads during VO₂ deposition. The film was deposited using a KrF excimer laser (Lambda-Physik LPX 200, λ = 248 nm) with a repetition rate of 10 Hz and a pulsed energy of 350 mJ focused on a rotating metallic vanadium target for 30 min. The deposition temperature was kept at 470 °C with an oxygen atmospheric pressure of 15 mTorr. After deposition, the sample was annealed for an additional 30 minutes under the same deposition conditions in order to improve the VO₂ stoichiometry. Fig. 2(b) shows two superimposed images of the MEMS actuator at both actuation limits, where a total deflection of approximately 80 μm was measured. The quality of the VO₂ film was verified by temperature dependent resistance measurements through the Pt electrodes exposed to the VO₂ layer. The typical VO₂ hysteretic resistance curve was observed, similar to those shown in [2], [4], and [12] - the curve is not shown in the manuscript to conserve space.

B. Measurement Setup

In order to characterize the device and perform the control experiments, the chip holding the micro-actuator was placed in an integrated circuit (IC) package and the electrical pads to the Pt heater and the VO₂ connections were wire bonded. The IC package was then placed on a custom-made PCB board, which contained the electrical traces to access the device. Fig. 2(a) shows the schematic representation of the measurement setup used for characterizing and controlling the actuator. A charge-coupled device (CCD) camera was used for aligning a near infrared laser diode (λ = 808 nm) with the tip of the actuator. The reflected light from the laser was focused into the active area of a position sensitive detector (PSD) (Hamamatsu S3270) whose output voltage (V_d) is proportional to the incident light from the laser. The voltage was connected to a field programmable gate array (FPGA) and a data acquisition (DAQ) system, in order to monitor the deflection of the actuator. In the FPGA/DAQ, V_d was converted to the device deflection by performing a linear fit of the relationship between tip displacement and V_d at various Pt heater current values. The output of the FPGA/DAQ was connected to the integrated Pt heater in order to drive the actuator through Joule heating by supplying a current (I_h). The FPGA/DAQ was programmed to actuate the device in open or closed-loop and was used to obtain all the measurements shown in this work. A computer was used to interface with the FPGA/DAQ, change setpoint values, and extract the data.

It is noted that, although the described measurement setup serves well for the studies on feedback control presented in this work, its overall size could seem somewhat impractical for most applications. Undergoing research efforts are focused on the use of self-sensing approaches in order to realize more compact closed-loop control systems.

III. Device Characterization

The measurement setup shown in the previous section was used to characterize the actuator in terms of quasi-static tip response, frequency response, transient response, creep,
repeatability, and rate dependence. This characterization is essential, not only to obtain crucial information for the controller design, but also, to understand the working principles of the micro-actuator and how it can be optimized to achieve desired performance specifications.

A. Quasi-Static Analysis

For obtaining the tip displacement as a function of current, an increasing-decreasing stair-case current sweep, from 0 to 4.7 mA in steps of 0.03 mA, was applied to the integrated heater to electro-thermally drive the actuator. Each setpoint duration was set to 10 s (4 s of wait time, which were used to ensure the deflection reached steady-state, and 6 s of hold time, during which the deflection signal was averaged). Fig. 3 shows the tip displacement as a function of current through the Pt heater. A similar behavior to that of previous experiments is observed, which is dominated by a non-monotonic hysteresis [1], [2], [4], [13]. The mechanisms responsible for such behavior (large deflection and non-monotonic behavior) are explained in detail in [1], where the abrupt and large positive change in deflection has been demonstrated to be produced by the structural phase transition of the VO$_2$ film. As the VO$_2$ goes through the transition, its crystallographic plane parallel to the SiO$_2$ contracts abruptly, producing compressive stress that pulls the device upwards. The non-monotonic behavior is due to the competing mechanisms during actuation. During the transition, the effect of the structural phase transition largely dominates the effects of the different thermal expansion coefficients; whereas the thermal expansion coefficient difference is the only active mechanism outside this phase-transition region. These two mechanisms generate bending in different directions, producing the non-monotonic behavior observed in Fig. 3. An example of an electrothermal MEMS actuator, where the displacement is generated solely by the different thermal expansion coefficients of the structural materials can be found in [14].

The maximum observed deflection for the increasing current direction was found to be approximately 82 $\mu$m, which was different than the 80 $\mu$m observed in the SEM images due to the viewing angle. A larger deflection of approximately 95 $\mu$m was observed through the current decreasing direction. The maximum controllable deflection chosen in this work was 82 $\mu$m due to the difficulties in controlling non-monotonic curves with a simple PID. At this maximum deflection the current and voltage were 3.64 mA and 1.28 V, respectively, resulting in a heater resistance value of 353.33 $\Omega$ and a power dissipation of 7.155 mW. It is important to note that the resistance value calculated here includes the Pt trace to and from the heater, although the trace resistance is smaller due to its larger geometries.

B. Frequency Response

The frequency response of the micro-actuator was obtained by applying a frequency varying sinusoidal current signal with adjustable offset and amplitude to the Pt heater while measuring the deflection amplitude. An offset and amplitude values of 2.75 mA and 0.75 mA were chosen, respectively, since the region of interest to be controlled is during the VO$_2$ film transition and these values result in the highest deflection gain (see Fig. 3).

Fig. 4 shows the gain of the micro-actuator, defined here as $\mu$m/mA, as a function of frequency. The behavior of the frequency response resembles that of a first order transfer function with a maximum magnitude of 45.5 $\mu$m/mA at low
results revealed a simulated electrothermal cut-off frequency of 42.7 Hz (268 rad/s), where \( f_{ce} \) is defined as the frequency where the magnitude is 0.707 times of the magnitude at DC. A plot of the model fitted with the experimental data is also shown in Fig. 4 and will be explained in detail in the following section.

To determine the mechanism limiting the performance of the actuator, an electro-thermal time-dependent finite element method (FEM) simulation was performed using COMSOL Multiphysics [15]. The material parameters for heat capacity at constant pressure \( C_p \), density \( \rho \), thermal conductivity \( k \), and electrical conductivity \( \sigma \) used in the simulation are summarized in Table I. Common thermal properties were used for SiO\(_2\), Pt and air, while for VO\(_2\), values found in literature were adopted [16], [17]. The electrical conductivity of Pt was modeled as a function of temperature due to its highly temperature dependence [4], which can be approximated by \( \sigma (T) = 8.9 \times 10^{7}/(1 + 0.0037297) \). Using the geometry of the micro-actuator described previously, the results revealed a simulated electrothermal cut-off frequency \( f_{ce} \) of 34 Hz, which is relatively close to \( f_{ce} \). Thus, the mechanism limiting the performance of the micro-actuator in this work is the thermal dissipation through the device anchor and surrounding media, which is in accordance with previous work [4], [12].

C. Time Response

Another important experiment that reveals dynamic characteristics of the device is the time response of the micro-actuator. For this experiment, current steps were given to the heater while the tip deflection of the device was being monitored. The sampling rate for this experiment was 20 kHz, which is much larger than \( f_{ce} \). The measured deflection throughout a series of current steps is shown in Fig. 5. From the insets, the time constants associated with the increasing and decreasing steps were calculated to be 3.5 ms and 3.7 ms, respectively. Although their values are very similar, the differences may be due to the different system boundary conditions in both cases — there is no active cooling in the device — and the asymmetry of the deflection hysteresis. Similar behavior have been observed in [12].

Another observed feature from Fig. 5 is the slow steadystate transient for decreasing current changes, which could be attributed to slower cooling time constants. Creep is known to be a temperature dependent process, increasing with increasing temperature, which is the opposite of what is observed in this experiment. A consequence of creep is permanent performance degradation [18] due to dislocations and material fatigue, which is not observed to happen for the VO\(_2\)-based MEMS actuator studied in this work (see Section III-D). In a previous work, the authors did not find evidence of creep nor differences between heating and cooling in VO\(_2\)-coated Si cantilevers [13]. The actuation mechanism used in [13] was orders of magnitude slower than the thermal transients in the micro-device, which made the differences between heating and cooling transient unnoticeable. In this work, the micro-actuator thermal transients dominate the time response of the device, and thus, the differences between heating and cooling boundary conditions are more evident. This evidence suggests that the observed slow cooling transients might be due to differences in boundary conditions between heating and cooling rather than material creep.

D. Reliability

Reliability is a measure of similarity between two separate measurements under same conditions and measurement setup, which accounts for variations in measurement setup and device performance. The latter includes fatiguing, fracture, and degradation of the micro-actuator, while the former is related to vibrations and environmental disturbances. For achieving accurate control of the micro-actuator, it is important that both, measurement setup and the device performance, are repeatable and reliable.

To show the reliability of the VO\(_2\)-based MEMS actuator, a quasi-static deflection measurement was taken five days after all the measurements in this work were completed and after the device was pulsed in open-loop for hundreds of thousands of cycles. Fig. 6(a) shows this quasi-static result along with the data of the experiment in Fig. 3. Fig. 6(b) shows the error between the two quasi-static sweeps for both increasing and decreasing current plots. The error for the increasing sweep is between 3.8 and \(-2.75 \mu m\) with an average of 0.69 \(\mu m\), and for the decreasing sweep is between 3.2 and \(-2.25 \mu m\) with an average of 1.2 \(\mu m\). Both graphs are almost identical with differences probably due to random vibrations or other environmental noises, which shows that the VO\(_2\)-based MEMS actuator and the measurement setup can produce reliable and repeatable results even after hundreds of thousands of cycles with no noticeable degradation. It should be noted that, given the stability of VO\(_2\) the micro-actuator presented here is not expected to show reliability issues due to film degradation (i.e. stoichiometry changes) for the operating conditions involved in the present work.

![Fig. 5. Deflection time response of the micro-actuator through a series of current steps. Two inset figures showing increasing (heating) and decreasing (cooling) steps were added to the figure for visualizing their differences.](image)
E. Rate Dependency

Rate-dependent hysteresis is produced by a phase lag between input and output signals as a result of the system dynamics. This phase lag in conjunction with the memory effect due to the hysteresis produces a change in the input-output relationship, which strongly depends on the frequency of the input. Although this mechanism has been observed in the past in micro-actuators [19]–[21], it has never been observed in VO₂-based actuators.

To study this effect in the device used in this work, a sinusoidal current input was applied to the Pt heater in the actuator with amplitude of 0.68 mA and offset of 2.68 mA at different frequencies while measuring its deflection. The results for some of the frequencies are shown in Fig. 7. The response at low frequencies (0.1 Hz) is similar to the quasi-static experiment results, but, as the frequency is increased, the output-input relationship starts changing. At 10 Hz the hysteresis is significantly wider although its amplitude seems unaffected, and at 50 Hz the amplitude has already decreased almost half of its original value while the hysteresis becomes even wider. From here and up to 200 Hz the amplitude continues to decrease while the hysteresis shape completely shifts to the other side — at low frequencies higher currents produced higher deflections while at higher frequencies lower currents produced higher deflections. This effect (change in the direction of deflection as the frequency is increased) is due to the system dynamics, and has been observed in the past in magnetostrictive actuators [19].

Hysteretic nonlinear models and control schemes, such as hysteresis compensation, would increase modeling accuracy, but, due to the complicated system dynamics and hysteresis behavior shown, this approach would be highly computationally intensive. In addition, the observed rate dependency must be considered in closed-loop control if incorporating hysteresis compensation schemes, which requires an even increased level of modeling and computational complexity. The control schemes needed to incorporate these effects would be outside the scope of the computationally efficient modeling and control techniques proposed in this work, which is aimed at demonstrating closed-loop control of VO₂-based MEMS actuators using PID control. The authors have included a supplementary color wmv file, which contains a video showing the deflection as a function of heater current for different current frequencies in order to show the rate-dependence of the micro-actuator. The video is available to download at http://ieeexplore.ieee.org.

IV. Theory

Using the results obtained from the device quasi-static and dynamic characterizations, and after demonstrating device and setup reliability, the device can be modeled and controlled. Rather than utilizing complex modeling and control schemes, the proposed approach in this work is to show that VO₂-based MEMS actuators can be accurately controlled through a simple, yet effective PID controller.

A. Dynamic Model of the Actuator

The micro-actuator model in this work consists of a first-order transfer function representing the electro-mechanical component, which is derived from the experimental results in Fig. 4, plus a second-order transfer function representing air drag and damped resonance, which is derived theoretically and validated through a FEM simulation. From the experimental results on frequency response as shown in Fig. 4, it was observed that the micro-actuator can be modeled by a first order transfer function with a cut-off frequency determined by the thermal dynamics in the device. The general expression for a first order transfer function is:

\[ A_{th}(s) = \frac{A_0}{\tau s + 1}, \]  

where \( A_0 \) is the DC gain and \( \tau \) is the time constant of the micro-actuator. In this work the gain at 0.1 Hz was assumed as the DC gain since it was orders of magnitude higher.

Fig. 6. Reliability test results for the VO₂-based MEMS actuator. (a) Quasi-static deflection as a function of current before and after all the experiments. (b) Error between both curves for the increasing and decreasing current sweeps.

Fig. 7. Deflection as a function of sinusoidal current input at different frequencies. The shape of the hysteresis is dependent on the actuation frequency showing the rate dependency of the micro-actuator.
The transfer function of a damped harmonic oscillator is defined as:

\[ A_{\text{drag}}(s) = \frac{k_{\text{eff}}}{s^2 + \frac{\beta_a}{m_{\text{eff}} + \rho a} s + \frac{k_{\text{eff}}}{m_{\text{eff}} + \rho a}}, \]  

where \( k_{\text{eff}} \) is the effective spring constant of the device obtained from [22], [23], \( m_{\text{eff}} \) is the effective mass \( (m_{\text{eff}} = 33/144 m) \) where \( m \) is the actual cantilever mass calculated from the densities and volume of the materials, and \( \beta_a \) and \( \beta_0 \) are the acceleration and velocity drag coefficients, respectively. These coefficients are defined as [24]:

\[ \beta_a = 6\pi \eta R \left( 1 + R \sqrt{\frac{2\rho \omega}{\rho \omega}} \right), \]

\[ \beta_0 = \frac{2}{3} \rho R^3 \left( 1 + \frac{9}{2R} \sqrt{\frac{2\eta}{\rho \omega}} \right), \]

where \( \rho \) and \( \eta \) are the density and dynamic viscosity of the medium surrounding the micro-actuator, which in this case is air, \( R \) is the radius of the sphere used to model the micro-actuator, following the procedure detailed in [25], and \( \omega \) is the angular frequency. All of the material parameters used for the calculations are shown in Table I and the derived coefficients are shown in Table II. Although \( \beta_a \) and \( \beta_0 \) are a function of \( \omega \), (2) can be approximated by another second-order transfer function \( \hat{A}_{\text{drag}}(s) \) with coefficients obtained through a parameter fitting in order to approximate \( A_{\text{drag}}(s) \) effectively with coefficients independent of \( \omega \). Here, \( \hat{A}_{\text{drag}}(s) \) results in:

\[ \hat{A}_{\text{drag}}(s) = \frac{\omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}, \]

where \( \omega_n \) is defined as the natural frequency of the micro-actuator, and \( \zeta \) is defined as the damping ratio. The obtained values from the model fitting were \( \omega_n = 39898.2 \text{ rad/s} \) and \( \zeta = 0.05 \). To study the accuracy of the approximated model, the magnitude of (2) and (5) were compared where a maximum error of 0.1% was observed through a frequency range from 0.1 Hz to 100 kHz. To further validate the approximated model, a natural frequency of 41202 rad/s was obtained from a FEM eigenfrequency simulation of the micro-actuator using the material parameters in Table I. The error between the analytically calculated angular frequency to that obtained from the simulation is 5%. Equations (1) and (5) can be multiplied to obtain the overall transfer function of the VO2-based MEMS micro-actuator and substituting all of the parameters in the resulting transfer function yields:

\[ A_{\text{MA}}(s) = \frac{1.8767 \times 10^{13}}{(s + 263.2)(s + 1.995 \times 10^3 \pm j3.985 \times 10^3)}, \]

Fig. 8 shows the bode plot (magnitude and phase) of the micro-actuator transfer function in (6). The resulting system has a gain margin \( GM = -5.64 \text{ dB} \), which clearly states that the system would be closed-loop unstable for any proportional gain greater than 0.34. This limit is observed experimentally, although it shows at a slightly lower gain, probably due to the approximations used in the model. The system also has multiple crossover frequencies that result in three phase margins of \( \Phi M = 90.7^\circ, 65.5^\circ, \) and \(-53^\circ\). Using this approximated model, which consisted of the experimentally identified thermo-mechanical model and the theoretically derived air drag and harmonic model, a PID controller can be designed and implemented for closed-loop control of the micro-actuator.

### TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_0 ) (( \mu \text{m}/\text{mA} ))</td>
<td>44.8</td>
</tr>
<tr>
<td>( \tau ) (ms)</td>
<td>3.8</td>
</tr>
<tr>
<td>( R ) (( \mu \text{m} ))</td>
<td>95.5</td>
</tr>
<tr>
<td>( k_{\text{eff}} ) (N/m)</td>
<td>0.0606</td>
</tr>
<tr>
<td>( m_{\text{eff}} ) (kg)</td>
<td>( 3.25 \times 10^{-11} )</td>
</tr>
</tbody>
</table>
VO₂ actuator deflection \( y \) while meeting specific performance requirements.

The transfer function of the PID control derived through the Laplace transform is defined as:

\[
K(s) = K_p + \frac{K_i}{s} + K_d s,
\]

where \( K_p, K_i, \) and \( K_d \) are the proportional, integral and derivative gains of the controller, respectively. The values of these gains are chosen as to obtain a desired system performance in terms of frequency and transient response while ensuring zero steady-state error. In the process of obtaining the gains in this work it was noticed that the micro-actuator closed-loop response showed steady-state oscillations with frequency and amplitude strongly dependent on the controller gains. This effect has been observed in the past for hysteretic systems controlled in closed-loop and has been attributed to limit cycles produced by the hysteresis [26]–[28]. Another observation is that the amplitude and frequency of limit cycles increase with increasing \( K_p \) [26], which is in accordance with what is observed in this work. As mentioned in [26], it is difficult to determine the effect of the controller gains in the limit cycle behavior through an analytical study, and thus, an experimental approach is used in order to determine a set of controller gains that reduce the limit cycles while accurately controlling the micro-actuator.

In this work, two PID controllers (PID₁ and PID₂), with bandwidths more than half a decade apart, are designed, implemented and compared. Bandwidths of \( f_c₁ = 70 \text{ Hz} \) and \( f_c₂ = 500 \text{ Hz} \) are chosen in order to stay well below the resonant frequency while achieving relatively fast actuation transients. In addition, a maximum overshoot of 1% is required, which corresponds to a phase margin of 173° for both controllers. This overshoot limit is chosen to show the applicability of this technology to micro-manipulation, where large deviations from the setpoint are undesirable. The gains for the resulting controllers are shown in Table III and the controllers transfer functions are given by:

\[
K_1(s) = 1.05 \times 10^{-4} \left(\frac{s + 872.7}{s} + 127.3\right), \tag{8}
\]

\[
K_2(s) = 1.05 \times 10^{-4} \left(\frac{s + 2276}{s} + 390.4\right). \tag{9}
\]

![Fig. 9. Closed-loop deflection control diagram for the VO₂-based MEMS actuator.](image)

<table>
<thead>
<tr>
<th>Gain</th>
<th>PID₁</th>
<th>PID₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_p )</td>
<td>0.105</td>
<td>0.28</td>
</tr>
<tr>
<td>( K_i )</td>
<td>11.66</td>
<td>93.31</td>
</tr>
<tr>
<td>( K_d )</td>
<td>( 1.05 \times 10^{-4} )</td>
<td>( 1.05 \times 10^{-4} )</td>
</tr>
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</table>

![Fig. 10. Closed-loop bode plots for the system in Fig. 9 using the two PID controllers.](image)

The resulting closed-loop transfer functions for the system in Fig. 9 using both controllers are shown in Fig. 10. It is observed that for the system with \( K_1(s) \) the bandwidth and phase margin are 72 Hz and 173°, respectively, while for \( K_2(s) \) these values are 496 Hz and 168.7°. These results show that both controllers meet the design requirements and will be used to study the VO₂-based MEMS actuator performance under closed-loop control. For implementing the closed-loop controller a sampling time of 10 \( \mu \text{s} \) was used, which is sufficient enough to ensure complete signal reconstruction.

V. RESULTS AND DISCUSSION

To determine the performance of the PID controllers designed in the previous section, a series of tracking experiments are performed. A step reference tracking experiment is used to study the transient characteristics of the closed-loop system and the effect of the controller gains in the limit cycles. Another experiment is performed in order to study the tracking performance of the system under sinusoidal-modulated reference signal at different frequencies. Finally, a comparison between open-loop and closed-loop control of the micro-actuator under temperature disturbance is done to demonstrate the need of accurate closed-loop control.

A. Step Reference Tracking

In this experiment, a total of six increasing and decreasing steps were applied to the input of the system in order to study the transient and steady-state performance of the micro-actuator. Each step size was 21 \( \mu \text{m} \) with duration of 0.5 s and the total controlled range was 65 \( \mu \text{m} \). Fig. 11(a) shows the setpoint and measured deflection of the micro-actuator as a function of time under PID₁. It is observed that the deflection of the device follows the desired deflection path effectively and the deflection is maintained during steady-state. The inset in Fig. 11(a) shows the transient of the deflection signal, characterized by a time constant of 2.42 ms, which is close to the 2.2 ms approximated from the model and simulated.
controller. In addition, no overshoot was observed in the signal as required by the design specifications. The error of the signal, in \( \mu m \), is shown in Fig. 11(b) where the average steady-state error observed was zero, due to the integral part of the PID. The average of the closed-loop maximum errors were \( \pm 1.4 \) and \( 2.7 \mu m \) for PID1 and PID2, respectively (for the maximum displacement range of \( 80 \mu m \)). The insets on this plot show evidence of the steady-state limit cycles produced by the hysteresis. It is observed that the peak-peak error is setpoint-dependent with a maximum of \( 3.8 \mu m \). In addition to the error amplitude, the error frequency is also observed to be setpoint-dependent. These dependencies with setpoint values are thought to be due to the asymmetric hysteresis observed in Fig. 3, which changes the shape of the resulting limit cycles –thus, the peak-peak errors are dependent on the input set-points and on the initial deflection before the set-point is applied. These effects can also be noticed in the control effort shown in Fig. 11(c) where an interesting feature is the difference in effort amplitude and frequency between increasing and decreasing set points for the same deflection value.

Fig. 12 shows the step reference tracking results using PID2. The first difference to notice between the deflection performance in Figs. 12(a) and 11(a) is the noisier signal of the former, which is produced by the higher bandwidth (higher \( K_p \)) obtained with PID2. The second difference is the faster transient times obtained with PID2, which results in a time constant of \( 0.34 \) ms, although higher transient oscillations are observed since \( K_p \) in this controller is closer to the stability maximum. A third difference for PID2 is the amplitude and frequency of the steady-state oscillations observed in the deflection error in Fig. 12(b). Although the average steady-state error is zero, similar to the results with PID1, the maximum peak-peak error is \( 5.75 \mu m \), which is \( 1.5 \times \) larger than that of PID2. In addition, the frequencies of these oscillations seem to have increased with PID2. These results are in agreement with previous observations where the frequency and amplitude of the steady-state limit cycles increase with increasing \( K_p \) [26]. The effect of the higher gains is also observed in the controller effort in Fig. 12(c), which is substantially higher than with PID1. These results show that closed-loop control of VO2-based MEMS actuators can achieve fast transient responses while minimizing deflection overshoot and average steady-state error. Depending on the performance specifications, different controllers can be designed and implemented to take advantage of the large displacements produced by these actuators.

B. Sinusoidal Reference Tracking

In some cases, micro-actuators are operated under time varying reference inputs, such as sinusoidal signals. To study the frequency performance of the micro-actuator under PID control using both controllers designed in this work, the frequency of a sinusoidal reference input is varied across a large deflection range while the deflection is been monitored. The amplitude and offset of the reference signal are \( 25 \mu m \) and \( 35 \mu m \), respectively. Fig. 13 shows the results obtained in this experiment using PID1 up to a frequency of \( 10 \) Hz at which the response has a phase lag of approximately \( 8.3^\circ \). This phase lag is in agreement with the model and PID predictions observed in the bode plots in Fig. 10. The results also show the effective control of the micro-actuator throughout the frequencies studied. One observable trend is that the error at the sinusoidal peaks tends to increase for increasing frequencies. This might be due, not only to the phase lag, but also to the non-monotonic deflection, as can be seen from the measured deflection signals near the sinusoidal peaks.

Fig. 14 shows the results of the sinusoidal tracking experiment with the PID2 controller. These results show a better performance of the micro-actuator at higher frequencies, which results in smaller errors, while higher errors are observed at lower frequencies, possibly due to the higher proportional gain. The deflection of the micro-actuator accurately tracks
Fig. 13. Sinusoidal reference tracking results at different frequencies for the micro-actuator under PID 1 control.

Fig. 14. Sinusoidal reference tracking results at different frequencies for the micro-actuator under PID 2 control.

the desired deflection up to 50 Hz with almost no phase lag. These results are again validated by the frequency response of the simulated system and controller in Fig. 10. Similar to the response under PID 1, the non-monotonic behavior of the micro-actuator is noticeable at the sinusoidal peaks.

In order to compare both results in terms of deflection error, the root-mean-square error (RMSE) is calculated. The RMSE in this work is defined by:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N} e(n)^2}{N}}$$  \hspace{1cm} (10)

where $e$ is the error calculated from the difference of desired and measured deflection, and $N$ is the number of elements in $e$. Fig. 15 shows the RMSE as a function of frequency calculated from the sinusoidal tracking experiments for the system under PID 1 and PID 2 control. At low frequencies the RMSE under PID 1 is significantly lower than the RMSE under PID 2, but as the frequency is increased, the RMSE under PID 1 increases exponentially whereas the RMSE under PID 2 has a much gradual linear slope. This effect is likely due to the higher bandwidth of PID 2, although the larger RMSE observed for PID 2 at lower frequencies might be due to the higher amplitude for the limit cycles in this case.

For better visualization of the closed-loop control of the VO2-based MEMS actuator under step and sinusoidal reference tracking, the authors have included a supplementary color wmv file, which contains a video showing real-time actuator deflection as a function of time as well as a sideview live feed of the micro-actuator. The video is available to download at http://ieeexplore.ieee.org.

C. Open vs Closed-Loop Response

In this experiment, a Peltier heater was placed directly underneath the microactuator chip in order to simulate temperature disturbances. The temperature was controlled in closed-loop and temperature steps where given to the Peltier while the deflection of the micro-actuator, the current passing through the Pt integrated heater and the temperature at the sample were being monitored. Fig. 16(a)–(c) shows the deflection, heater current and temperature as a function of time with the micro-actuator under open-loop – constant current – and closed-loop control – constant deflection reference of 35 μm. Note that for the closed-loop control the PID 1 controller was used. The results show an evident superiority of closed-loop for controlling the deflection in temperature variant environments. Through the 20 °C temperature change, the deflection under open-loop underwent a change of 45 μm, which is undesirable for real-life applications. By using closed-loop control, the system was able to maintain the 35 μm deflection throughout the complete temperature disturbance range.
To further show the capabilities of the closed-loop controlled micro-actuator, a sinusoidal tracking reference input with a frequency of 0.1 Hz was applied to the system while the sample temperature was varied. Fig. 17(a)–(c) show the effectiveness of the control system throughout the complete actuation range even with a temperature disturbance of more than 15 °C. As long as the sample temperature does not exceed 25 °C, the control system can provide no overshoot and maintaining the micro-actuator at a desired deflection. The controller would supply the required current to maintain such deflection.

VI. CONCLUSION

The design and implementation of a closed-loop system comprising a VO₂-based MEMS actuator with an integrated heater have been developed in order to accurately control the large deflections produced by these devices through the use of Joule heating. A comprehensive characterization and modeling of the micro-actuator was performed and used to tune two PID controllers whose performance were compared through step reference, and sinusoidal reference tracking experiments. Finally, a temperature disturbance experiment was performed in order to show the advantages of closed-loop control over open-loop actuation. All of these results showed that VO₂-based MEMS actuators can be used for highly precise micro-manipulation and micro-positioning applications in temperature varying environments while achieving fast actuation, no overshoot and minimizing the deflection error. The use of other control algorithms and hysteresis inverse compensation could improve the closed-loop operation of these devices. In addition, other micro-actuator designs, such as smaller dimensions and optimum heater position, can be engineered to produce faster closed-loop actuation while maintaining the large deflections observed in these actuators.

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