Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators

Mathias Poik, Dominik Kohl and Georg Schitter

***Abstract*— The positioning accuracy of piezoelectric transducers is limited by nonlinearities such as hysteresis and creep. Improving the accuracy by feedback control is not always desired or possible due to the difficult integration of a position sensor. The method presented in this paper uses two piezoelectric transducers of the same type, to linearly operate one of them without a sensor. The nonlinear voltage-displacement relation of two transducers is analyzed and compared. It is shown that their nonlinearities are almost identical. The displacement of one of the transducers is measured and used to control the displacement of the other one, reducing the positioning error due to nonlinearities for a triangular reference signal from 9.2 % to 0.3 % of the actuation range.**

I. Introduction

Piezoelectric transducers (piezos) are widely used in nanopositioning applications, such as scanning stages for Atomic Force Microscopes (AFM) [1] and deformable mirrors for adaptive optics [2]. Advantages of piezos are their sub-nanometer positioning resolution, as well as their high bandwidth and forces. The major drawback is the nonlinear relation between the applied voltage and the resulting displacement, which shows a distinct hysteresis [3]. Depending on the piezoelectric material, the hysteresis can lead to positioning errors of up to 20 % of its range. Additionally, piezos suffer from creep [4], which is a slow process, especially apparent for applied voltage steps. After a step, the displacement keeps increasing logarithmically [5]. Without compensation, these nonlinearities between voltage and displacement lead to significant positioning errors.

A common approach for linear operation is the use of inverse models for hysteresis [6] and creep [7]. The main advantage of this approach is that no position sensor is required, and a high positioning bandwidth can be achieved due to the open-loop control structure [8]. However, without position measurement the actual displacement of the piezo is unknown, and unavoidable model uncertainties typically limit the positioning accuracy to 1 % - 3 % of the actuation range [9], [10]. Additionally, accurate nonlinear models are computationally expensive and require an extensive identification process due to their complexity.

It is known for several decades that the relation between the electric charge and displacement is almost linear [11]. This can be used to control the charge instead of the voltage of a piezo [12]. Charge control can lead to a significant reduction of hysteresis, without the need of a position sensor [13]. However, the remaining nonlinearities between charge and displacement (typically 1 %-2 % of the actuation range) impair the accuracy of charge controlled piezos [14]. Although a recent implementation showed a reduction of the positioning error to 0.4 % [15], its applicability for low frequency or DC operation is limited by leakage currents in the piezoelectric material, which is a general limitation of charge controlled piezos [16]. Although this problem can be circumvented by sensor fusion [17], this again requires an additional sensor.

Automation and Control Institute (ACIN), TU Wien, Gusshausstrasse 27-29, 1040 Vienna, Austria. Email: poik@acin.tuwien.ac.at

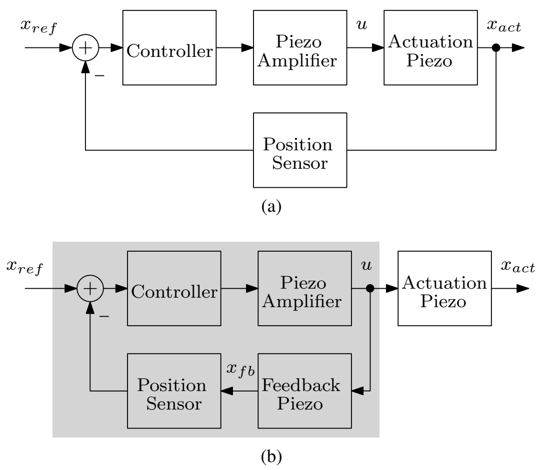

Fig. 1: Block diagram of (a) typical feedback control and (b) similarity-based feedback control for the compensation of nonlinearities. In (b), no displacement measurement of the Actuation Piezo is required.

When a position sensor is applicable, the displacement of the piezo can be measured and controlled by means of a feedback controller [18], [19] (Fig. 1a), leading to an excellent positioning accuracy, limited only by accuracy, noise and bandwidth of the sensor. However, position sensors with low noise, high accuracy and high bandwidth are in general rather bulky, and therefore difficult to integrate in some positioning systems [20]. Deformable mirrors for adaptive optics can contain hundreds or thousands of piezos with small inter-actuator pitch [2], and therefore no space is available for bulky position sensors. AFM tube-scanners are usually incorporated in a rigid and compact structure, in order to avoid the excitation of undesired resonances [21], [22]. It is therefore difficult to integrate position sensors for feedback control in these applications.

The contribution of this paper is the proposal and imple-

Post-print version of the article: M. Poik, D. Kohl, and G. Schitter, "Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators", *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2018. DOI: 10.1109/AIM.2018.8452310

mentation of a control scheme to reduce the nonlinearities of a piezo, based on the similarity of two piezos of the same type. The piezo which performs the actual positioning task is operated in open loop. As shown in Fig. 1b, a second, external piezo is operated with the same voltage, thus performing the same motion. This externally mounted piezo is easily accessible by a position sensor. Its displacement is measured and used for feedback control. As a result, no position measurement of the piezo that performs the actual positioning task is required anymore. Prior to the implementation of the control scheme, the paper presents a comparison of the nonlinear voltage-displacement relation of two piezos of the same type.

The proposed control scheme is presented in Section II. The similarity of two piezos of the same type is analyzed in Section III. Section IV describes the experimental implementation of the control scheme, and the experimental results are presented in Section V. Concluding remarks are given in Section VI.

II. Similarity-based Feedback Control

Fig. 1a shows a block diagram of the typical feedback control scheme used for the compensation of nonlinearities. The displacement x_{act} of the piezo (Actuation Piezo) is measured by a position sensor and fed back to a controller. This control scheme can only be applied if the displacement of the piezo can be directly measured by the sensor.

In the proposed similarity-based feedback control scheme shown in Fig. 1b, two piezos of the same type are used to overcome this limitation. The Feedback Piezo is operated by conventional feedback control. The Actuation Piezo, which performs the actual positioning task, is operated in open loop with the same voltage u and therefore performs the same motion. In opposite to typical feedback control, a direct measurement of x_{act} is not required anymore. The Feedback Piezo can be mounted externally and its displacement x_{fb} can therefore easily be measured by a position sensor.

A prerequisite for the effectiveness of the control strategy is that the nonlinear voltage-displacement relation of Actuation Piezo and Feedback Piezo are similar. Therefore, the voltage-displacement relation of the two piezos is analyzed and compared prior to the implementation.

A. Used actuators

In this work, two stack piezos of the type MPO-050015 (NanoFaktur, Villingen, Germany) are used. They have a nominal range of 15 μm at a maximum driving voltage of $U_{max} = 150$ V, a length and cross-section of 10 mm and 5×5 mm, respectively, and a nominal capacitance of 720 nF. For the comparison of their nonlinearities, the piezos are operated in open-loop without any feedback controller, as shown in Fig. 2. The analyzed piezos are denoted as Piezo A and Piezo B. The signals are generated and acquired by a data acquisition unit (NI-USB6211, National Instruments, Austin, USA) and the piezos are driven in parallel by a high bandwidth low-noise piezo amplifier (TechProject,

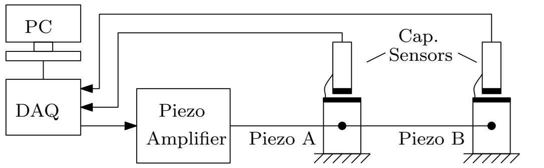

Fig. 2: Experimental setup for the comparison of the piezos used for the implementation of similarity-based feedback control. The two piezos are operated with the same voltage and their displacements are simultaneously recorded by capacitive distance sensors.

Vienna, Austria). Two capacitive distance sensors (Model-6810, MicroSense, Massachusetts, USA) are used to record the displacement of both piezos simultaneously. To reduce the influence of temperature fluctuations and environmental vibrations, the setup is covered by a custom-made temperature isolation box which is mounted onto an optical table. The noise of the measured displacement equals 0.96 nm_{RMS} with a drift of less than 7 nm over a period of 1 hour.

III. Similarity of used actuators

The major factor limiting the accuracy of piezo-based positioning systems is the distinct hysteresis, which depends on amplitude and frequency of the applied voltage [6]. In the following, sinusoidal signals of different amplitudes and frequencies are applied to the piezos. Parameters quantifying their nonlinear voltage-displacement relation are defined, which enables an estimation of the positioning accuracy of the system presented in Section II.

A. Actuation range

Due to production tolerances the actuation ranges of piezos of the same type can show significant differences. For the piezos used in this work, the manufacturer specifies a tolerance of ± 10 %. For the control scheme proposed in this work, a difference between the actuation ranges of the piezos would lead to a positioning error and has to be compensated by a scaling factor (see Section V). In order to enable a comparison of the relative nonlinearities, the displacements of the piezos are therefore normalized by their actuation ranges.

In this work, the actuation range is defined as peak-peak value of the displacement for an applied sinusoidal voltage with an amplitude of $U_{max}/2$ and an offset of $U_{max}/2$ at a frequency of 10 Hz. Fig. 3 shows one period of the displacement x_A of Piezo A and x_B of Piezo B. The ranges of Piezo A and Piezo B are $R_A = 11.6\,\mu$m and $R_B = 11.1\,\mu$m, respectively, which gives a difference of 4.5 %. The normalized displacements $\bar{x}_A$ and $\bar{x}_B$

$$\bar{x}_A = \frac{x_A}{R_A}, \quad \bar{x}_B = \frac{x_B}{R_B} \qquad (1)$$

enable a comparison of the relative nonlinearities.

Post-print version of the article: M. Poik, D. Kohl, and G. Schitter, "Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators", *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2018. DOI: 10.1109/AIM.2018.8452310

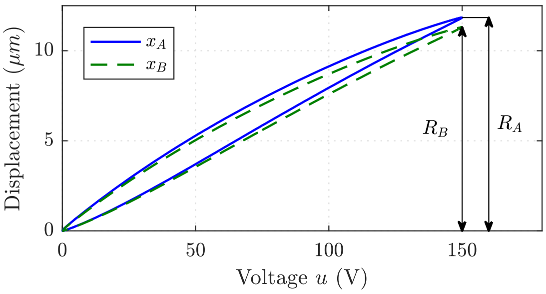

Fig. 3: Measured actuation ranges of Piezo A and Piezo B. The ranges show a difference of 4.5 %.

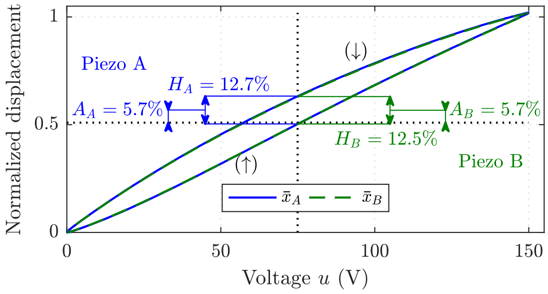

Fig. 4: Measured Hysteresis and Asymmetry of Piezo A and Piezo B. The shape of the normalized hysteresis curves is almost identical.

TABLE I: Difference of Hysteresis and Asymmetry between Piezo A and Piezo B for different frequencies.

	Frequency (Hz)			
	1	5	10	50
$H_A - H_B\,(\%)$	0.2	0.2	0.3	0.4
$A_A - A_B\,(\%)$	0.0	0.0	-0.1	-0.1

B. Hysteresis and Asymmetry

Fig. 4 shows the normalized displacements of the compared piezos for a sinusoidal voltage with an amplitude of $U_{max}/2$, an offset of $U_{max}/2$ and a frequency of 1 Hz. For the quantification of the normalized hysteresis curves, Hysteresis H is distinguished from Asymmetry A (which also includes saturation effects). Hysteresis H is defined as difference between descending (↓) and ascending (↑) branch of the normalized displacement at $u = U_{max}/2$:

$$H = \bar{x}\left(\frac{U_{max}}{2}\downarrow\right) - \bar{x}\left(\frac{U_{max}}{2}\uparrow\right). \quad (2)$$

Asymmetry A is the difference of the center of the hysteresis curves from from the center of the displacement range:

$$A = \frac{\bar{x}\left(\frac{U_{max}}{2}\downarrow\right) + \bar{x}\left(\frac{U_{max}}{2}\uparrow\right)}{2} - \frac{\bar{x}_{pp}}{2}, \quad (3)$$

where $\bar{x}_{pp}$ denotes the peak-peak value of the normalized displacement.

Piezo A and Piezo B show a Hysteresis of $H_A = 12.7\,\%$ and $H_B = 12.5\,\%$, as well as an Asymmetry of $A_A = 5.7\,\%$ and $A_B = 5.7\,\%$, respectively. With a difference of $H_A - H_B = 0.2\,\%$ for Hysteresis and an identical Asymmetry, the shapes of the hysteresis curves of the two piezos are almost identical. Both parameters are also measured for sinusoidal signals with frequencies of 5, 10, and 50 Hz. The differences of the parameters of the two piezos are depicted in Table I.

C. Amplitude dependence

The amplitude dependence of the hysteresis curves is analyzed by applying a sinusoidal amplitude sweep with a constant offset of $U_{max}/2$ to the piezos. The frequency of the applied voltage is 1 Hz. Hysteresis and Asymmetry of the compared piezos are shown in Fig. 5. It can be seen

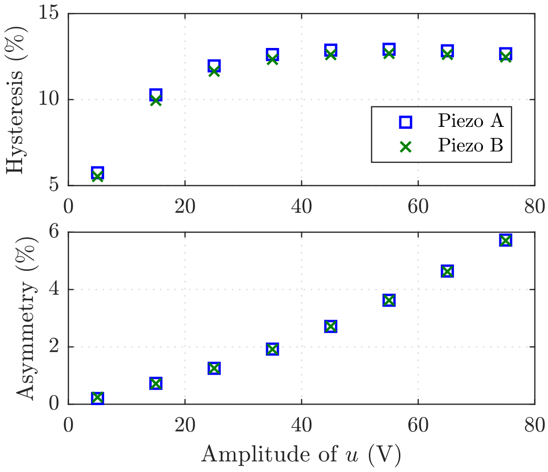

Fig. 5: Measured Hysteresis and Asymmetry of the two piezos depending on the amplitude of the applied voltage.

that the amplitude dependence of the parameters quantifying the hysteresis curves is similar. Hysteresis of the two piezos differs by only 0.4 % or less, and Asymmetry shows a maximum difference of only 0.1 %.

Summarizing the results presented in this section, the relative nonlinearities of the two analyzed stack piezos of the same type are almost identical. This is shown by normalizing the displacements of the piezos using their actuation ranges. Although the ranges show a difference of 4.5 %, the defined parameters quantifying the relative nonlinearities show a difference of only 0.4 % or less. It is therefore expected that the displacement of one piezo can be used to control the displacement of the other one, as proposed in the control scheme presented in Section II. The results are not restricted to the stack piezos introduced in the beginning of this section. The same analysis was carried out for stack piezos from a different vendor (NAC2013-A01, Noliac, Kvistgaard, Denmark), yielding similar results (data not shown).

Post-print version of the article: M. Poik, D. Kohl, and G. Schitter, "Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators", *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2018. DOI: 10.1109/AIM.2018.8452310

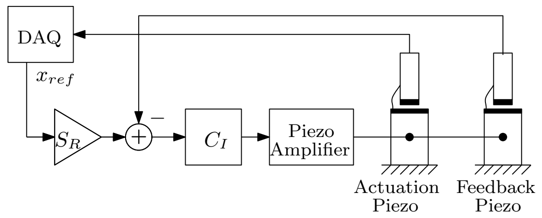

Fig. 6: Experimental implementation of similarity-based feedback control.

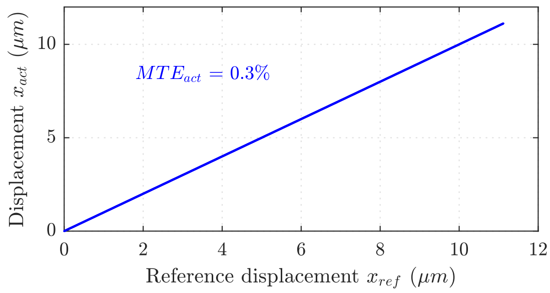

Fig. 7: Measured displacement of the Actuation Piezo operated by similarity-based feedback control, showing a highly linear response.

IV. Experimental Implementation and Controller Design

The similarity-based feedback control scheme (Fig. 1b) is implemented using the two piezos analyzed in the previous section. To this end, the setup shown in Fig. 2 is extended by feedback control. Piezo A thereby serves as Actuation Piezo and Piezo B as Feedback Piezo. The experimental implementation of similarity-based feedback control is shown in Fig. 6.

As shown in Section III-A, the ranges of the two piezos differ by 4.5 %. However, their relative nonlinearities are almost identical. It is therefore expected that the displacements x_{act} and x_{fb} of Actuation Piezo and Feedback Piezo are equal up to the scaling factor S_R

$$S_R = \frac{R_B}{R_A}. \tag{4}$$

In order to compensate for the range difference, the reference displacement x_{ref} is therefore multiplied by S_R. The measured displacement x_{fb} of the Feedback Piezo is subtracted from the scaled reference signal and the resulting control error is applied to a feedback controller C_I.

In this work, a custom-made integral controller

$$C_I(s) = \frac{k_I}{s} \tag{5}$$

is used. The gain k_I is tuned manually by a commonly used heuristic approach [25]. It is first increased until ringing occurs, then it is decreased by 10 %, such that the bandwidth is relatively high while maintaining closed-loop stability. The resulting closed-loop bandwidth equals 1.3 kHz (data not shown).

For the implementation of the proposed control scheme, the piezos are operated without mechanical load in this work. Although in a practical implementation the Actuation Piezo would be acting against a mechanical load, in many nanopositioning applications the applied load is small and its influence is negligible [23], [24].

V. Experimental Results

The accuracy of the proposed positioning system is investigated by applying the same sinusoidal signals as in Section III. Fig. 7 shows the displacement x_{act} of the Actuation Piezo for a sinusoidal reference displacement x_{ref} with an amplitude of $R_{act}/2$ at a frequency of 1 Hz. The displacement shows an almost linear response with a maximum tracking error MTE_{act}

$$MTE_{act} = \frac{|x_{ref} - x_{act}|}{\max(x_{ref}) - \min(x_{ref})} \times 100\% \tag{6}$$

of 0.3 %.

TABLE II: Maximum tracking error of the Actuation Piezo operated by similarity-based feedback control depending on the frequency (first row). The maximum tracking error of the Feedback Piezo (second row) is subtracted to eliminate the influence of the phase lag introduced by the feedback loop (third row).

	Frequency (Hz)			
	1	5	10	50
MTE_{act} (%)	0.3	0.4	0.6	3.0
MTE_{fb} (%)	0.0	0.2	0.5	2.6
$MTE_{act} - MTE_{fb}$ (%)	0.3	0.2	0.1	0.4

The measured error for frequencies of 5, 10 and 50 Hz is shown in the first row of Table II. For increasing frequencies MTE_{act} significantly increases. This can be explained by the phase lag introduced by the feedback loop which leads to a significant tracking error. To show that the increasing error at higher frequencies is mainly due to this phase lag, the maximum tracking error MTE_{fb} of the Feedback Piezo (replace x_{act} by x_{fb} in (6)), which experiences the same phase lag, is subtracted from MTE_{act} in the third row of Table II. The measured errors are close to the expected errors due to the difference of the hysteresis curves of the piezos presented in Section III-B.

To investigate the accuracy for different amplitudes, a sinusoidal amplitude sweep of the reference signal at a frequency of 1 Hz is applied. The tracking error is determined for each amplitude. As shown in Fig. 8, MTE_{act} equals 0.4 % or less, which is in accordance with the results presented in Section III-C.

Many piezo-based positioning systems, such as scanning stages for AFM, are commonly operated with triangular reference trajectories. The positioning accuracy is therefore evaluated for a triangular reference signal. The reference

Post-print version of the article: M. Poik, D. Kohl, and G. Schitter, "Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators", *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2018. DOI: 10.1109/AIM.2018.8452310

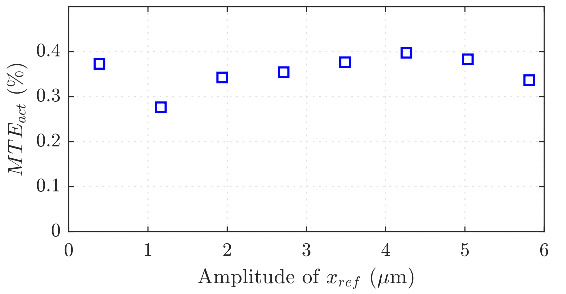

Fig. 8: Maximum tracking error of the Actuation Piezo operated by similarity-based feedback control depending on the amplitude of the applied reference signal.

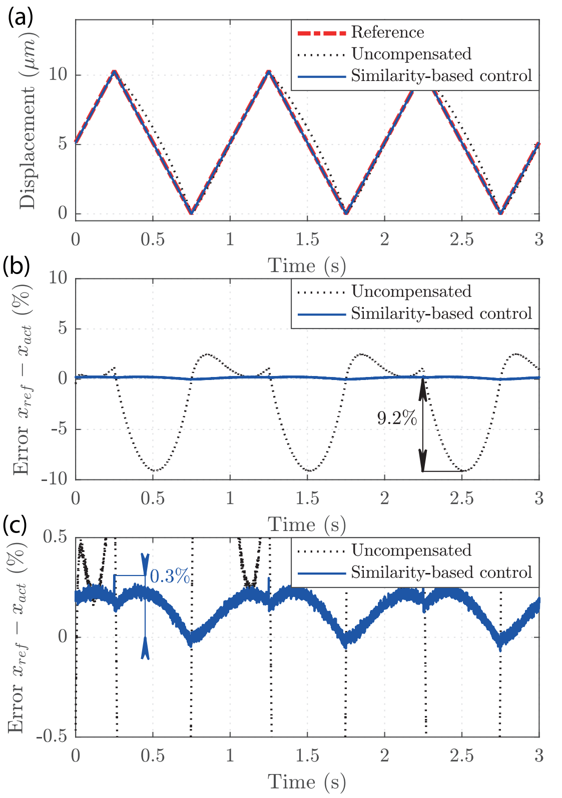

Fig. 9: Positioning accuracy for triangular trajectory: (a) Reference trajectory and measured displacement of Actuation Piezo with and without compensation of nonlinearities by similarity-based feedback control, (b)(c) comparison of positioning errors with and without compensation.

signal x_{ref} and the measured displacement of the Actuation Piezo x_{act} with and without similarity-based feedback control are shown in Fig. 9a. The corresponding positioning errors $x_{ref} - x_{act}$ are shown in Fig. 9b, and with different scaling in Fig. 9c. Without compensation for nonlinearities, the displacement shows an MTE_{act} of 9.2 %, i.e. 1.07 μm.

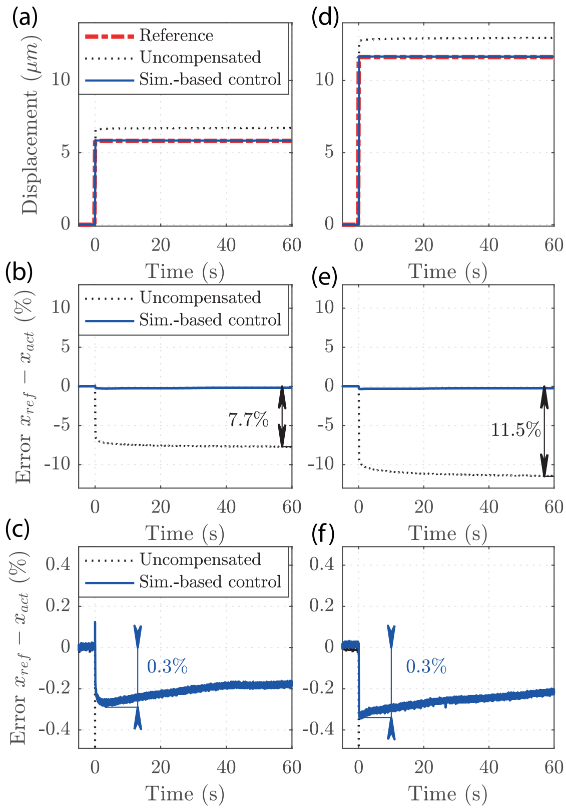

Fig. 10: Positioning accuracy for step trajectories: (a) Reference trajectory for step height of $R_{act}/2$ and measured displacement of Actuation Piezo with and without compensation of nonlinearities by similarity-based feedback control. (b)(c) Comparison of positioning errors with and without compensation. (d) Displacements and (e)(f) comparison of positioning errors for step height of R_{act}.

With similarity-based feedback control, MTE_{act} is reduced to 0.3 %, i.e. 36 nm.

A major challenge for low frequency or DC operation of piezos is the drift of the displacement due to creep [8]. Creep occurs for almost all signal shapes, but is especially apparent for step signals. The positioning accuracy is therefore investigated for steps of x_{ref}. Fig. 10a shows x_{ref} for a step height of $R_{act}/2$, together with x_{act} with and without compensation of nonlinearities by similarity-based feedback control. The resulting tracking errors are shown in Fig. 10b, and with different scaling in Fig. 10c. Without compensation, x_{act} shows a significantly higher step height than x_{ref} and therefore a large tracking error. Additionally, x_{act} slowly increases due to the creep behavior which leads to an error of 7.7 % of R_{act} after 60 s. With similarity-based feedback control, the error is reduced to 0.3 % and no significant drift of x_{act} is observed. Similar results are obtained for a step height of R_{act}, with a reduction of the error from 11.5 % to

Post-print version of the article: M. Poik, D. Kohl, and G. Schitter, "Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators", *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2018. DOI: 10.1109/AIM.2018.8452310

0.3 % (Fig. 10d-f).

In summary, it has been shown that the similarity of two stack piezos of the same type can be utilized to operate one of them linearly (positioning error $\leq 0.4\,\%$) in open-loop, by applying a driving signal which is generated by operating the second piezo in closed-loop.

VI. Conclusions

The control scheme presented in this paper operates a stack piezo linearly without co-located position measurement. The nonlinearities of two piezos of the same type are analyzed and compared. It is shown that the nonlinearities are almost identical, differing only by about 0.4 % of the actuation ranges of the piezos. By utilizing this property, the displacement of one piezo is controlled by feeding back the measured displacement of the other piezo. As a result, the positioning error for a triangular reference signal with a frequency of 1 Hz is reduced from 9.2 % to 0.3 % of the actuation range of the piezo. For the implementation of the control scheme no special care is taken during the selection of the piezos, other than using two piezos of the same type from the same vendor. Since the remaining positioning error arises from the difference of the nonlinearities of the piezos, it is expected that it can be reduced even further by using piezos with matched nonlinearities for the implementation of the proposed control scheme. Future work therefore includes the comparison of the nonlinearities of a larger number of piezos.

Acknowledgments

This work was supported by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) under the scope of the Austrian Space Applications Program (project number 854050).

References

[1] G. Binnig and C. F. Quate, "Atomic Force Microscope," *Physical Review Letters*, vol. 56, no. 9, pp. 930–933, 1986.
[2] I. Kanno, T. Kunisawa, T. Suzuki, and H. Kotera, "Development of Deformable Mirror Composed of Piezoelectric Thin Films for Adaptive Optics," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 13, no. 2, pp. 155–161, 2007.
[3] D. Damjanovic, "Hysteresis in piezoelectric and ferroelectric materials," in *The Science of Hysteresis*. Elsevier, 2006, vol. 3, pp. 337–465.
[4] H. Jung and D.-g. Gweon, "Creep characteristics of piezoelectric actuators," *Review of Scientific Instruments*, vol. 71, no. 4, pp. 1896–1900, 2000.
[5] S. Vieira, "The behavior and calibration of some piezoelectric ceramics used in the stm," *IBM journal of research and development*, vol. 30, no. 5, pp. 553–556, 1986.
[6] M. A. Janaideh, S. Rakheja, and C. Y. Su, "Experimental characterization and modeling of rate-dependent hysteresis of a piezoceramic actuator," *Mechatronics*, vol. 19, no. 5, pp. 656–670, 2009.
[7] H. Janocha and K. Kuhnen, "Real-time compensation of hysteresis and creep in piezoelectric actuators," *Sensors and Actuators, A: Physical*, vol. 79, no. 2, pp. 83–89, 2000.
[8] D. Croft, G. Shedd, and S. Devasia, "Creep, hysteresis, and vibration compensation for piezoactuators: atomic force microscopy application," *Proceedings of the American Control Conference*, vol. 3, no. June, pp. 2123–2128, 2000.
[9] M. Al Janaideh and P. Krejčí, "Inverse rate-dependent Prandtl-Ishlinskii model for feedforward compensation of hysteresis in a piezomicropositioning actuator," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 5, pp. 1498–1507, 2013.
[10] G. Y. Gu, L. M. Zhu, and C. Y. Su, "Modeling and compensation of asymmetric Hysteresis nonlinearity for Piezoceramic actuators with a modified Prandtl-Ishlinskii model," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 3, pp. 1583–1595, 2014.
[11] R. H. Comstock and A. West, "Charge Control of Piezoelectric Actuators o reduce hysteresis effects," U.S. Patent No. 4,263,527. 21 Apr., 1981.
[12] C. Newcomb and I. Flinn, "Improving the linearity of piezoelectric ceramic actuators," *Electronics Letters*, vol. 18, no. 11, p. 442, 1982.
[13] K. A. Yi and R. J. Veillette, "A charge controller for linear operation of a piezoelectric stack actuator," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 517–526, 2005.
[14] D. Kohl, S. Hoser, R. Saathof, and G. Schitter, "Budgeting of Systematic Versus Stochastic Errors in Sensor Fusion for Piezo Electric Transducers," in *Preprints of the 20th World Congress*, 2017, pp. 7912–7917.
[15] C. Yang, C. Li, and J. Zhao, "A Nonlinear Charge Controller with Tunable Precision for Highly Linear Operation of Piezoelectric Stack Actuators," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 8618–8625, 2017.
[16] A. J. Fleming and S. O. R. Moheimani, "Hybrid Dc Accurate Charge Amplifier for Linear," *IFAC Proceedings Volumes*, vol. 37, no. 14, pp. 277–282, 2004.
[17] A. J. Fleming, A. G. Wills, and S. O. R. Moheimani, "Sensor fusion for improved control of piezoelectric tube scanners," *IEEE Transactions on Control Systems Technology*, vol. 16, no. 6, pp. 1265–1276, 2008.
[18] G. Schitter, P. Menold, H. F. Knapp, F. Allgöwer, and A. Stemmer, "High performance feedback for fast scanning atomic force microscopes," *Review of Scientific Instruments*, vol. 72, no. 8, pp. 3320–3327, 2001.
[19] S. Salapaka, A. Sebastian, J. P. Cleveland, and M. V. Salapaka, "High bandwidth nano-positioner: A robust control approach," *Review of Scientific Instruments*, vol. 73, no. 9, pp. 3232–3241, 2002.
[20] A. J. Fleming, "Quantitative scanning probe microscope topographies by charge linearization of the vertical actuator," *Review of Scientific Instruments*, vol. 81, no. 10, pp. 26–30, 2010.
[21] A. J. Fleming and S. O. Reza Moheimani, "Sensor-less vibration suppression and scan compensation for piezoelectric tube nanopositioners," *IEEE Transactions on Control Systems Technology*, vol. 14, no. 1, pp. 33–44, 2006.
[22] S. Kuiper and G. Schitter, "Active Damping of a Piezoelectric Tube Scanner using Self- Sensing Piezo Actuation," *Mechatronics*, vol. 20, no. 6, pp. 656–665, 2010.
[23] H. Hu and R. Ben Mrad, "On the classical Preisach model for hysteresis in piezoceramic actuators," *Mechatronics*, vol. 13, no. 2, pp. 85–94, 2003.
[24] M. Rakotondrabe, "Bouc-Wen modeling and inverse multiplicative structure to compensate hysteresis nonlinearity in piezoelectric actuators," *IEEE Transactions on Automation Science and Engineering*, vol. 8, no. 2, pp. 428–431, 2011.
[25] D. Kohl, T. Riel, R. Saathof, J. Steininger, and G. Schitter, "Auto-tuning PI controller for surface tracking in atomic force microscopy - A practical approach," in *Proceedings of the American Control Conference*, 2016, pp. 7396–7401.

Post-print version of the article: M. Poik, D. Kohl, and G. Schitter, "Similarity-based Feedback Control for Linear Operation of Piezoelectric Actuators", *2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2018. DOI: 10.1109/AIM.2018.8452310