Characterization of stiction effects of an electrostatic micro positioner for probe storage

Mihai Pătraşcu and Stefano Stramigioli, Senior Member, IEEE
Control Engineering, Department of Electrical Engineering, University of Twente, Room 8252/8234 P.O. Box 217, 7500AE Enschede, The Netherlands
E-mail: {M.Patrascu, S.Stramigioli}@utwente.nl

Abstract. We start by presenting a short explanation of the micro actuator working principle. The main contribution of this paper is the characterization of the coefficient of stiction between two silicon nitride parts of a MEMS actuator. Having one flat contact surface while the other is composed of many relatively sharp circular bumps, has the advantage that the effective contact area is drastically reduced. The stiction coefficient varies between 0-0.53 for the device configuration presented. The exact value depends closely on the electrostatically applied force which presses the textured part on to the smooth one. Individual measurements used are highly accurate (typically within 5 nm noise band) and identical measurements for the characterization of stiction show only a small variation, typically under 25 nm on a range of 11.8 µm.

1. Introduction
One of the necessary components in probe storage is an actuator which controls the position of the data medium with respect to the tips used for reading and writing data. The MEMS actuator needed for such a task must be extremely reliable, have a life time in the order of years of normal operation and must perform constantly. So far, fabricating a device with such properties has proved rather difficult in MEMS.

Sometimes a miniaturized and decoupled 2D coil system is used in data storage [1]. As such magnetic actuators do not scale favorably towards smaller dimensions [2], other solutions were considered. In the μSPAM project, we aim at proving the feasibility of a probe storage device with electrostatic shuffle actuators [3]. Due to the reduced size of the actuator (about 1 mm² for the upcoming 2D version), the device can be composed of up to 100 independently working tiles, each of them featuring one electrostatic actuator for 2D positioning, a medium for holding data and a number of tips for read/write. This architecture brings a lot of opportunities for data redundancy, parallel read/write and further miniaturization. Former efforts within the μSPAM project include miniaturization of the magnetic medium [4], tip-sample approach, design and fabrication of the electrostatic actuator by using surface micro-machining and isolation trench technology [5], [6], [7], [8] and physical modeling [9], [10], [11].

In this article, we present some results from the characterization procedure of a one-dimensional actuator, the μWalker, which is the basic component for the 2D actuator to be used in the first prototype of μSPAM. The accent lies on the stick phenomena occurring at the actuator contact points with the surface it moves on. This is especially interesting, because we can reproducibly influence the stick behavior by altering the input voltage of the respective part. Some quantitative information about life time and wear is presented at the end of this work.

μSPAM stands for Micro Scanning Probe Array Memory, see http://www.uspam.nl
2. Device description and actuation principles

The μWalker device is composed of the following main parts (see Fig. 1(a)): two U-shaped legs, a large thin plate which can be attracted towards the surface, eight retraction springs and four short connection springs which connect the ends of the two legs. The walking principle sketched in Fig. 1(b) is used to make one or more steps in one direction. Basically, when the plate is attracted and released (in Fig. 1(b) the third and last sub-sequence from top to bottom, respectively), the leg which shifts will slightly slip over the surface. The basic idea is that the other leg should be as fixed as possible in order to maximize performance. Fixing the legs and attracting the plate is achieved by electrostatic actuation: by applying a voltage to either component, this component is attracted to the surface by an electrostatic force, as the bulk of the wafer is fixed to ground potential. If the order of the six sub-sequences is inverted, a step in the opposite direction results. One step (≈ 50 nm) can be repeated in order to obtain larger displacements, typically about 10 μm in both directions for the prototype presented here. The range is generally limited by the configuration and dimensions of the retraction springs. The dimensions of these springs can be altered according to the desired specifications. This and other actuation sequences are presented rigorously in [11].

3. Modeling the retraction springs

In [9] the middle plate of the μWalker is modeled from an energy balance point of view. The model predicts the step size and the necessary operating voltage. Stick and slip properties of the two legs have been implemented in a physical model for simulation purposes [10].

Of vital importance for the interpretation of the results in the next section are the retraction springs. These springs connect electrically the plate and the legs to bonds (marginally visible in Fig. 1(a)) and not to forget, they bring the μWalker back to the same position each time all inputs are set to zero voltage. This is an important condition for obtaining measurements with high accuracy and repeatability. By measuring the bending of the retraction springs, on the basis of elastic models we can derive several force characteristics of the μWalker actuator.

Let us consider the general case of a beam of constant rectangular cross-section between the ends, while the ends are fixed in both horizontal and vertical direction. In our case, because the μWalker is symmetric, each set of left and right retraction springs add up to one such beam. In line with [12], the total stiffness of one retraction spring, namely bending stiffness and axial stress, can be approximated by comparing the axial force to the buckling force of the structure. This is only valid if the deflection is in
the same order of magnitude compared to the thickness of the beam in the plane of motion, in this case $w_{\text{beam}}$. The following equations were derived for estimating the force due to a certain displacement at the center point of the beam:

$$F_{\text{bm.st.}} = k_{\text{bm.st.}} \Delta y,$$

$$k_{\text{bm.st.}} = \frac{E_{\text{poly}} w_{\text{beam}}^3 h_{\text{beam}}}{L_{\text{beam}}^3} \left[ 1 + \frac{36 (\Delta y)^2}{5 \pi^2 w_{\text{beam}}^2} \right]$$

(1)

with $E_{\text{poly}} = 160 \cdot 10^9 Pa$ the Young’s modulus for poly silicon, $F_{\text{bm.st.}}$ the spring counter force, $k_{\text{bm.st.}}$ the stiffness, $\Delta y$ the deflection, $L_{\text{beam}} = 200$, $w_{\text{beam}} = 2$, $h_{\text{beam}} = 5.5$ the length, width and height of the retraction spring in $\mu m$, respectively. The force depends on the cube of the displacement. This relation discounts for the fact that as the deflection increases, the spring counter force increases more than linear due to the increased axial force in the spring. Results from this model and work done by others\[8\] comply within 10% along the entire spring range.

4. Characterization of the stiction coefficient

The legs and plate in Fig.1(a) do not touch the walking surface entirely. Due to a regular texture of round small bumps, the contact area is practically reduced to only a few points, instead of the whole part area. At the same time, the electrostatically applied force does not change much due to the presence of the bumps. An optical setup with a fire-wire camera was used to capture the $\mu$Walker position each 33.3 ms. Sub-pixel resolution down to 5 nm can be obtained by monitoring the position of repetitive patterns in the picture, and running a script based on work presented in [13].

Consider now the measurement of Fig.2(a), where we can distinguish six sequential actions. All three input voltages are grounded during the first second in order to capture a number of frames at zero position. During the next two seconds, 500 steps into one direction are taken, to make sure that the maximum range has been reached; For 0.5 s, both legs are attracted to the surface by using a high constant voltage (55 V) – this actuation keeps the $\mu$Walker fixed at the maximum range.

The most important step is that now one leg is not actuated anymore (0 V), while the other has a constant voltage, in the example shown 20 V. Due to this, the vertical clamping force is not enough to compensate for the horizontal force exerted by the retraction springs on the structure, so the device slips back towards steady state position. The reduced mass of the device ($< 1.4 \cdot 10^{-9} kg$) excludes the presence of any noticeable dynamics so that the $\mu$Walker continues to slip towards the center, until an equilibrium has been reached again between the horizontal force due to friction and the horizontal counter force from all the counter springs together. When the equilibrium has been reached, the device comes in stick again, and this position is typical for the voltage applied during the present sequential action (20 V in this case). In the end, all inputs are set to ground and the measurement is stopped.
Now, we can repeat this sequence a number of times and a surprisingly good repeatability can be remarked: the standard deviation of the position while in stick for five consecutive trials is less than 15 nm! This type of measurements can be repeated for other voltages than 20 V, namely between 15 V and 35 V. The mean of the displacements obtained have been plotted in Fig.2(b), together with $\pm 3 \cdot STD$ as defined above, where STD stands for the standard deviation from general probabilistic theory. The vertically applied force on the different parts of the $\mu$Walker is given by:

$$F_{applied} = \frac{\varepsilon_0 \varepsilon_{Si} A_{part} V_{in}^2}{2d^2}$$

with $\varepsilon_{Si} / N = 7.6$, $A_{part}$ is the area of the leg or plate, $V_{in}$ is the applied voltage and $d$ is the effective distance between the plates.

By using Eq.2 and Eq.1, we can associate the relation between the displacements obtained and the applied voltages to a relation between the vertically applied force and the horizontally generated anti-slip force (Fig.3(a)). Deriving the coefficient of stiction is now straightforward, because the direction of the lines passing through origin and each point in Fig.3(a) corresponds exactly to the stiction coefficient $\mu_{stiction}$, which is valid for the respective point only (Fig.3(b) results).

The variation of the coefficient of stiction can be roughly explained by the fact that the ratio between the effective and apparent contact area varies with the applied voltage. The effective contact area is only a few bumps for low voltages, destructive inspection confirms this. As the voltage is increased, more contact points are added, which in turn increase the anti-slip force. Second order effects like for instance the exact shape of the bumps, material stiffness and the presence of wear in the system define the exact shape seen in the Fig.3(b).

5. Wear and life time

The expected life time and the change in performance with time are eminent problems which need attention, when this actuator is to be used in a probe storage system for instance. In this context, some extensive measurements were taken in order to estimate the life time and wear effects of the present $\mu$Walker prototype. The main target is to determine the serviceable life, or the life which is considered useful from the point of view of maximum range, velocity and repeatability.

such that the presence of bumps and the insulating layer have been discounted for.

the vertical counter force of the retraction springs was subtracted from the applied force $F_{applied}$, but the calculations have been omitted here due to lack of space.
Figure 4. Wear pattern after breaking some retraction springs and turning the μWalker upside down.

Figure 5. Mean and standard deviation of one step size up to total failure of the device.

The destructive measurement in Fig.4 shows signs of wear after about 75 million standard steps, an estimated 4m of displacement while moving up and down at 4mm/s. The most contact points are grouped in small clusters and can be observed at the corners. The horizontal and vertical patterns which can be observed on the silicon nitride walking surface are not of great importance, they are a result of small topographical differences in the order of a few nm due to etching of the sacrificial layer [7].

For a more quantitative wear measurement, another device was run at slower velocities and in a continuous fashion. At least once per day, the continuous movement was stopped and a standard movement (40 steps into one direction) was repeated ten times. From the final position, the mean step size and the standard deviation between the ten runs could be obtained, after which the continuous movement was restarted. The results are plotted in Fig.5 against the number of steps. These measurements took almost two weeks, after which the μWalker under attention did not function anymore.

Looking at Fig.5(b), it can be concluded that after $4.5 \cdot 10^9$ steps the variation of the end position in the test runs increased from under 3nm to above 37nm. Using the step size information from the test runs, a total distance of about 746m has been calculated ($1.83 \cdot 10^9$ steps). In [7], a distance of 1500m has been reported, which roughly agrees with the measurements presented here. In contrast with [7], a remarkable performance deterioration has been observed here.

Whether or not the end of the service life has been reached at this point, depends on the target
specifications. For the μSPAM project, using feed-forward control to control the μWalker would indeed mean the end of the service life, as the positioning accuracy of about 10nm is not met anymore and predictions about the exact position become too inaccurate. Although more measurements are needed to draw a final conclusion about the life time, the results presented above are an indication of the huge amount of steps that can be performed.

6. Conclusion
A method has been presented to experimentally determine the relation between coefficient of stiction and the vertically applied force between a smooth surface and a part which consists of equidistantly placed bumps. This coefficient is between 0 and 0.53 for the present design and materials used. Extended step reproducibility tests give an estimation of the μWalker life time. For the tested device and given the required positioning accuracy of about 10nm, the end of the life time emerged after 4.5·10⁹ steps.

Acknowledgments
The authors thank Edin Sarajlic for designing and fabricating the first version of the μWalker, as well as for the valuable insight regarding measurements. S. Vanapalli, who implemented the sub-pixel resolution software is also kindly acknowledged. This work part of μSPAM, which is an STW project (TES5178).

References
[1] T. Altebaumer, P. Bächold, G. Binnig, G. Cherubini, M. Despont, U. Drechsler, U. Dürrig, E. Eleftheriou, B. Gotsmann, W. Hüberle, C. Hagltenner, D. Jubin, M. Lantz, A. Pantazi, and E. H. Pozidis, “Thermomechanical data storage using large arrays of micromechanical probes,” Meccanica, pp. 1–14, 2005, for review only.
[2] M. J. Madou, Fundamentals of Microfabrication, 2nd ed. CRC Press, 2002, ISBN: 0-8493-0826-7.
[3] M. Bolks, F. Hanssen, L. Abelmann, P. Havinga, P. Hartel, P. Jansen, C. Lodder, and G. Smit, “Micro Scanning Probe Array Memory (μSPAM),” Proceedings of the Second Progress Workshop, Veldhoven, The Netherlands, pp. 17–26, October 2001, ISBN: 90-73461-26-X.
[4] R. Murillo, H. A. van Woulen, L. Abelmann, and J. C. Lodder, “Fabrication of patterned magnetic nanodot array memory by laser interference lithography,” Journal of Microelectronic Engineering, vol. 78, pp. 260–265, 2005.
[5] N. Tas, J. Wissink, L. Sander, T. Lammerink, and M. Elwenspoek, “Modeling, design and testing of the electrostatic shuffle motor,” Sensors and Actuators A, pp. 171–178, 1998.
[6] E. Sarajlic, E. Berenschot, H. Fujita, G. Krijnen, and M. Elwenspoek, “Bidirectional electrostatic linear shuffle motor with two degrees of freedom,” MEMS 2005 - 18th IEEE International Conference on Micro Electro Mechanical Systems, Miami, pp. 391–394, January 2005.
[7] E. Sarajlic, E. Berenschot, N. Tas, H. Fujita, G. Krijnen, and M. Elwenspoek, “High performance bidirectional electrostatic inchworm motor fabricated by trench isolation technology,” TRANSDUCERS 05 - Int. Conf. on Solid State Sensors and Actuators - Seoul, Korea, June 2005.
[8] E. Sarajlic, “Electrostatic microactuators fabricated by vertical trench isolation technology,” Ph.D. dissertation, University of Twente, The Netherlands, 2005, ISBN: 90-365-2212-9.
[9] N. E. Ligterink, M. Patrascu, P. C. Breedveld, and S. Stramigioli, “An energy-based electroelastic beam model for MEMS applications,” Sensors and Actuators A: Physical, vol. 121, no. 2, pp. 500–507, June 2005.
[10] M. Patrascu and S. Stramigioli, “Modeling and simulating the stick-slip motion of the uWalker, a MEMS-based device for uSPAM,” Micro System Technologies, December 2005, Accepted for publication.
[11] ——, “Stick-slip actuation of electrostatic stepper micropositioners for data storage- the uWalker,” ICMENS, July 2005.
[12] J. E. Mehner, L. D. Gabbay, and S. D. Senturia, “Computer-aided generation of nonlinear reduced-order dynamical macromodels - II: stress-stiffened case,” Journal of Microelectromechanical Systems, vol. 9, pp. 270–278, June 2000.
[13] S. Vanapalli, “Techniques for characterization of in-plane displacement for microactuators,” Master’s thesis, Department of Electrical Engineering, University of Twente, The Netherlands, 2004.