Actuators: Accomplishments, opportunities and challenges.

Frederik Ceyssens, Sina Sadeghpour, H Fujita, Robert Puers, …

1. Introduction

The world that surrounds us is purely analog. So, it is mandatory that the interfaces we create to communicate with this world are analog in nature. This is a typical aspect of transducers, that provide the transition of signals of the real world into electric signals for communication and vice versa. The first devices are called sensors, the second are the actuators. One cannot deny the massive influence the evolution of sensor and actuator technology over the course of the 20th century has seen by micro-and nanofabrication technology developed for integrated circuit (IC) manufacturing. A second and more recent development lies in the creation of advanced nanomaterials, which can also be applied in transducers.

While at present a vast variety of microsensor devices are successfully applied in a multitude of applications, the current portfolio of microactuators is more limited, as the force generated by MEMS actuators is often insufficient. Most successful examples deal with controlling light: digital mirror devices, optical switches, tunable lenses etc. Still, a sizeable amount of work exists in areas such as micropumps and microvalves, which are often essential for lab on chip and medical implant development. Further, successful thermal actuators can be found in the inkjet printing field, yielding spectacular results in terms of speed thanks to the scaling laws. In fact, there lies the core for success in MEMS actuators: exploring the advantages of the scaling effect. It allows to obtain unseen and intuitively unexpected performance in the electrostatic area, as well as well as in the area of thermal actuation. This puts the focus on finding niche markets where the small size not *per se* should be considered a disadvantage. Bolometers for IR imaging are a good example.
Another particular phenomenon that can yield excellent results is the piezoelectric effect, providing a good control on the formation of piezoelectric layers can be achieved. Table 1 gives an condensed overview of examples of applications for actuators.

Table 1 : Overview of typical applications for the different driving physics

force/ material / structure	electrostatic	magnetic	piezoelectric	thermal expansion	Electro-active polymer	fluidic force
sliding, rolling	micromotors wobble motor	electromagnetic micromotor				
flexure	parallel plate actuator comb-drive actuator DMD buckling actuator	moving coil actuator moving magnet actuator Magnetostrictive	bi/uni-morph beam piezo stack actuator	thermal expansion actuator thermo bimorph shape memory alloy	bimorph actuator	balloon actuator
friction drive	SDA actuator impact drive actuator		ultrasonic motor	artificial cilia		
levitation, etc.	electrostatic levitation gyroscope/accelerometer	super conductive levitation actuator		bubble jet printing		air levitation MHD,EHD electro osmotic flow

The scaling laws not always are favorable. Friction scales only with the second power of size, and limits the deployment of e.g. high speed rotating gears and micromotors using classical bearing designs[1]. Scaling is especially unfavorable for in electromagnetic devices, where the obtainable force scales to the fourth power of the size. Therefore, they are inferior at small scale compared to surface-dependent forces such as electrostatic attraction, which scales proportional to the second power of size. Obviously, this boosts the electrostatic actuation as the winner in microsystems. A God-given advantage of capacitive actuation is that it inherently provides the capacitance value between two movable plates, yielding a value for displacement. Moreover, the effects of gravity, scaling proportional the cube of size, become negligible compared to surface forces.[2].

A clear trend in the world of transducer research is the introduction of new, advanced materials. Though single crystal silicon is definitely still the workhouse of the industry, the plethora of new, often nanotechnology-enabled materials developed or under development has strong potential. Such materials include graphene, carbon nanotubes, nanoporous materials, 'smart' polymers (e.g. electroactive polymers, …) and so on. The result of several billions of years of evolution can be expected to be a good inspiration for the designers of one of the main technologies that will underpin the 21st century.

In the sections that follow, several actuation mechanisms from table 1 will be shortly discussed.

2. Electromagnetic actuation

We have already shown that electromagnetic forces are relatively weak at the microscale and below. Beside the earlier mentioned scaling problem, there exist several pending issues that block the breakthrough of the magnetic MEMS. High-power dissipation is one of them, since the magnetic field is current driven.[3] Further, a coil or a relatively bulky external permanent magnet is needed, that is hard to fabricate in the traditional IC technology, and it requires space. Moreover, at higher frequencies, parasitic losses become dominant, jeopardizing the efficiency of the coils. Integratability with the CMOS process is often cumbersome, and finally directivity may impose a limitation for certain applications.[4]

---

* This chapter is based on the paper presented at IEEE MEMS Conf. 2018: Hiroyuki Fujita, "From wow to work: Cycles of MEMS evolution", Proceedings Pages:141 - 144

[1] H Fujita 1997, "A decade of MEMS and its future" Proceedings of IEEE MEMS 1997

* This chapter is based on the paper presented at IEEE MEMS Conf. 2018: Hiroyuki Fujita, "From wow to work: Cycles of MEMS evolution", Proceedings Pages:141 - 144

[2] K. Eric Drexler, "Nanosystems," John Wiley & Sons, Inc., New York, 1992 Chapter 2, 'Classical Magnitudes and Scaling Laws,'

[3] H. Guckel, "Progress in Magnetic Microactuators", Microsystem Technologies (1998) 5: 59. https://doi.org/10.1007/s005420050141

[4] H.H. Gatzen, "Advances in European Magnetic MEMS Technology", (2002):, Proc. 7th Int. Symposium on Magnetic Materials, ECS 2002, Salt Lake City, UT, USA, pp. 90-108

3. Electrostatic actuators*

Electrostatic microactuators have advantages such as:
1) a favorable scaling for miniaturization,
2) on chip integration by IC-compatible micromachining using conventional materials,
3) easily controlled by electronics although high-voltage circuits are required sometimes,
4) they require very little power, especially with position holding mechanisms.
However, because they are vulnerable to environment, e.g. dust and moisture, they need to be encapsulated in packages. Therefore, the electrostatic actuators are suitable to produce motion that can be completed within the constraints of a chip. Such applications include servo feedback sensors, self-testing of inertial sensors, optical beam scanners and shutters, and positioning of heads and probes. Many configurations have been demonstrated, e.g. a parallel plate configuration, and an interdigitating comb-drive configuration. The movable part is supported by flexible suspensions in most cases to avoid friction. The instability of a flexible electrode deformed by electrostatic force must be taken into account carefully when you design movable structures. For example, the motion range of a parallel plate actuator is limited to 1/3 of its initial gap due to pull-in instability.
We will concentrate on the commonly used comb-drive actuator, and its bio application, i.e. the silicon nano tweezers.

3.1. COMB-DRIVE ACTUATOR

The comb-drive, that was first introduced by William C. Tang, et al. in Transducers 1989[5], utilizes transverse force to the major direction of the electric field and has a large displacement of a few tens of micrometers. The first device was made by surface micromachining out of 2-mirometer- thick polysilicon. The driving gap was 2 to 3 micrometers. They formed MEMS resonators with frequencies ranging from 18 to 80 kHz and a Q-factor from 20 to 130. Double-folded suspensions with connection bars were elegantly designed to avoid stiction due to the instability of interdigitated fingers. A good actuator should have a large stroke with a fast response; this means that the driving force must be large. Suppose the applicable voltage is limited, we need to increase the electrode thickness or to decrease the gap width.

3.1.1 Narrow gap device

Sub-micrometer gaps can be fabricated without sub-micrometer lithography and etching[6]. The basic idea is to make the first comb-teeth with a separation of a given width and to insert it into the opposing comb-teeth having the separation slightly wider than that of the first one. As a result, the gaps formed are quite small.
The analysis based on a simple model revealed that the instability of interdigitated fingers sticking to each other depends linearly on the overlapping length of fingers and inverse-cubically on the gap width. Hirano et al. carefully designed the suspension and obtained 10.6

---

[5] W. C. Tang, TC. H. Nguen, M. W. Judy and R. T. Howe, "Electrostatic-comb Drive of Lateral Polysilicon Resonators", Sensors and Actuators, A21 -A23 (1990) 328 -331

[6] T. Hirano, T. Furuhata, K. J. Gabriel, H. Fujita, "Design, Fabrication, and Operation of Submicron Gap Comb-Drive Microactuators", IEEE Jour. Microelectromechanical Systems, Vol. 1, No. 1, pp.52-59 (1992)

micrometers of motion at 22.2 V with a 500 nm gap. Resonant frequency was around 5 kHz. Much more detailed modeling and analysis were performed by the group of Prof. Miko Elwenspoek[7] for large displacement at low driving voltage. They compared various suspension designs. Models were obtained to analyze the lateral large deflection behavior of clamped–clamped beams and a folded flexure. They also derived expressions for the side-instability voltage and the resulting displacement at side instability. Their device produced deflections of about 30 micrometers at ~20 V with a resonance frequency of 1.6 kHz.

Deep reactive ion etching (DRIE) process was invented by Robert Bosch GmbH and patented in 1996[8]. Combined with silicon-on-insulator (SOI) substrates, it is one of the most commonly used technique to fabricate MEMS. Recent development allows us to obtain trenches with aspect ratio of 107, width of 374 nm and depth of 40 micrometers[9]. Thick comb-drive actuators with sub-micron gaps that produce a strong force can easily be made by this process.

3.1.2. Vertical comb-drive actuators

Usual comb-drive actuators move in plane. Some applications, e.g. a rotational scanning mirror, require out-of-plane motion. Interdigitated combs with different height or off-set can produce such a motion. Self-aligned subsequent DRIE was realized using the first etched structure to define the second etching patterns to produce interdigitated comb with different heights[10] [11] . Post processing steps were added to introduce an offset angle by tensile stress of photoresist hinges put on the upper surface[12] or a rotational silicon hinge with one edge pulled down by a stiction pad[13]. In the former case, offset angles of 20-40 degrees can be introduced to have optical scanning angles of +/-18 degrees with a 21V sinusoidal input at 1.4 kHz.

3.1.3. Applications

As was initially intended, the comb-drive was used for high-Q resonators with potential application to RF circuits[14]. CMOS compatibility of the device is the attractive feature of silicon

---

[7] R. Legtenberg, A. W. Groeneveld, M. Elwenspoek, “Comb-drive Actuators for Large Displacements”, J. Micromech. Microeng. 6 320–329 (1996).

[8] Robert Bosch GmbH, Patent 5501893, March 26 (1996)

[9] F. Marty, L. Rousseau, B. Saadany, B. Mercier, O. Francais, Y. Mita, T. Bourouina, “Advanced Etching of Silicon based on Deep Reactive Ion Etching for Silicon High Aspect Ratio Microstructures and Three-dimensional Micro- and Nanostructures”, Microelectronics Journal, 36 (2005) 673–677

[10] U. Krishnamoorthy, O. Solgaard, “Self-aligned Vertical Combdrive Actuators for Optical Scanning Micromirrors,” Proc. 2001 IEEE/LEOS Int. Conf. on Optical MEMS (Optical MEMS 2001), 25-28 Sept., 2001, Okinawa, Japan, pp. 41-42.

[11] E.T. Carlen, Khee-Hang Heng, S. Bakshi, A. Pareek, C. H. Mastrangelo, “High-aspect Ratio Vertical Comb-drive Actuator with Small Self-aligned Finger Gap”, IEEE Jour. of Microelectromechanical Systems, Vol. 14, No. 5, pp. 1144-155 (2005).

[12] P. Patterson, D. Hah, H. Chang, H. Toshiyoshi, M.C. Wu, “An Angular Vertical Comb Drive Actuator for Scanning Micromirrors,” Proc. 2001 IEEE/LEOS Int. Conf. on Optical MEMS (Optical MEMS 2001), 25-28 Sept., 2001, Okinawa, Japan, pp. 25-26.

[13] K. Isamoto, T. Makino, A. Morosawa, C. Chong, H. Fujita, and H. Toshiyoshi : “Self-Assembly Technique for MEMS Vertical Comb Electrostatic Actuators,” IEICE Electronics Express Vol. 2, No. 9, pp.311-315 (2005).

[14] Clark T.-C. Nguyen, Roger T. Howe “An Integrated CMOS Micromechanical Resonator High- Oscillator”, IEEE Jour. Solid-State Circuits, Vol. 34, NO. 4, 440-455 (1999)

resonators as compared to conventional quartz resonators. The most successful application is vibrational angular rate gyroscope. The suspended proof mass is driven by the comb-drive actuator to vibrate at its resonance. When rotational motion occurs around the axis perpendicular to the vibrating mass, vibration in orthogonal direction is induced. The amplitude of the induced vibration yields information on the rotational speed. ST Microelectronics has created very successful products of multi-axis inertial sensors, including the vibrational gyroscope[15].

The optical scanning mirror driven by the vertical comb-drive actuator was applied to optical coherence tomography[16]. More exotic application is a MEMDAC device that converts a 12-bit digital input (45 V) to analogue displacement output over 8.6 micrometers with 4096 positions in ~2 nm steps[17].

3.1.4. Evolution to vibrational energy harvester

When a voltage is applied, the comb-drive device produces a displacement. On the contrary, when the suspended mass in the comb-drive device is driven by an external force or acceleration, it produces output power if two electrodes are polarized at different electrical potential. An electret layer, in which electrical charge is fixed, can provide such a built-in potential, and avoids the need for an externally applied DC bias voltage.

An electret film was formed between the interdigitating comb-electrodes separated by a microscopic gap[18]. After DRIE patterning, the gap was thermally oxidized with potassium-ion-doping. The resultant SiO_2 film was polarized at ~500 degree-C with a bias voltage of 100 to 400 V in vacuum; this voltage is maintained after cooling.

As an example, we have developed two types of energy harvesters. One is to produce a large power in the 1 mW range at relatively high acceleration of ~1 G at 50 to 100 Hz[19]. The other is to collect a faint vibration of a few tens of mG at low frequency in the ~10 Hz range[20]; this device adopts a symmetric configuration composed of a pair of polarized comb-drives to cancel out the electrostatic force that constrains the movable electrodes from starting vibration.

3.2. SILICON NANO TWEEZERS

---

[15] http://www.st.com/content/st_com/en/about/innovation---technology/mems.html

[16] M. Nakada, C. Chong, A. Morosawa, K. Isamoto, T. Suzuki, H. Fujita, and H. Toshiyoshi: "Optical Coherence Tomography by All-optical MEMS Fiber Endoscope," IEICE Electronics Express, vol. 7, no. 6, pp. 428-433 (2010)

[17] E. Sarajlic, D. Collard, H. Toshiyoshi, H. Fujita, "Design and Modeling of Compliant Micromechanism for Mechanical Digital-to-Analog Conversion of Displacement" IEEJ Trans 2007; 2: 357–364. DOI:10.1002/tee.2015

[18] G. Hashiguchi, D. Nakasone, T. Sugiyama, M. Ataka, H. Toshiyoshi, "Charging Mechanism of Electret Film made of Potassium-Ion-Doped SiO2", AIP Advances 6, 035004 (2016); http://doi.org/10.1063/1.4943528

[19] H. Honma, H. Mitsuya, G. Hashiguchi, H. Fujita, and H. Toshiyoshi, "Improvement of Effectiveness and Output of Electret Energy Harvester by Symmetric Comb-Drive Structures," in Proc. Power MEMS 2017, November 14-17, 2017, Kanazawa, Japan.

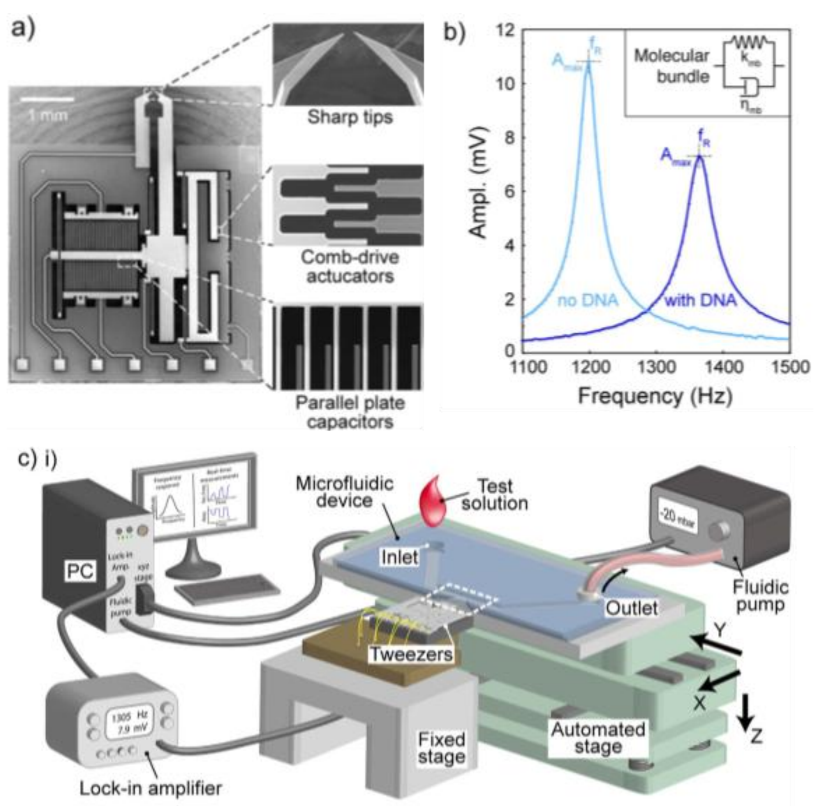
[20] H. Koga, H. Mitsuya, T. Sugiyama, H. Toshiyoshi, G. Hashiguchi, "1mW Output Electrostatic Vibratory Power Generator Allowed by Optimization of the Proof Mass" Proc. 16th Int. Conf. PowerMEMS 2016, Dec. 6-9, 2016, Paris, France.

3.2.1. Initial Device

MEMS devices can be miniaturized to the same size as biological cells, since their smallest features and motions are in nanometer range. Therefore, micromachined tools are useful to perform scientific analysis of biological cells and molecules. A pair of probes with 10-50 nm tip radius were micromachined with integrated microactuators. The device was applied to silicon nano tweezers (SNT) that handle DNA molecules. The initial device had sharp tips at the end of arms that were driven by thermal microactuators[21]. The sharp tips of SNT were coated with aluminum and dipped in an aqueous solution of DNA. A high frequency electric field (~1 MV/m at ~1 MHz) between tips attracted molecules, some of which were captured as a molecular bundle. We successfully retrieved it from the solution to the air and bent/stretched it.

3.2.2. Nano tweezers with a displacement sensor

The thermal actuator was replaced by a comb-drive actuator in the second generation device. A displacement sensor based on a differential capacitance configuration was integrated (Fig. 1 a). Those improvements allowed us to measure the mechanical characteristics of the trapped molecules (stiffness, viscosity) by the change in the resonant frequency characteristics of SNT with a DNA bundle (Fig. 1 b). A microfluidic device with a side opening was fabricated for the optimal performance of the tweezers to operate at the air-liquid interface for performing bioassays in liquid while actuating/sensing in air (Fig. 1 c)[22]. The minimal immersion of the MEMS device in the channel provided long-term measurement stability (>10 h). The method allowed real-time monitoring of the effects of multiple solutions on the same DNA bundle without compromising the reproducibility. We monitored two different types of effects on the mechanical responses of DNA bundles (stiffness and viscous losses) exposed to pH changes (2.1 to 4.8) and different Ag+ concentrations (1 μM to 0.1 M).



---

[21] G. Hashiguchi, T. Goda, M. Hosogi, K. Hirano, N. Kaji, Y. Baba, K. Kakushima, H. Fujita, "DNA Manipulation and Retrieval from an Aqueous Solution with Micromachined Nanotweezers", Analytical Chemistry, 75, pp.4347-4350 (2003)

[22] M. C. Tarhan, N. Lafitte, Y. Tauran, L. Jalabert, M. Kumemura, G. Perret, et al., "A rapid and Practical Technique for Real-time Monitoring of Biomolecular Interactions using Mechanical Responses of Macromolecules," Scientific Reports, vol. 6, p. 28001, doi:10.1038/srep28001

Figure 1: (a) Silicon nano tweezers, (b) resonant measurement, (c) setup with fluidic and electrical equipment [18].

3.2.3. Applications

Tumor cell elimination by X-ray beams in cancer radiotherapy is currently based on a rather empirical understanding of the basic mechanisms and effectiveness of DNA damage by radiation. We conducted real-time biomechanical measurement of the degradation of a DNA bundle in solution when exposed to a therapeutic radiation beam[23]. The SNT and associated microfluidic devices can endure the harsh environment of radiation beams and still retains molecular-level accuracy.
The experiments utilized a Cyberknife, a LINAC accelerator mounted on a robot arm at the Centre Oscar Lambret in Lille, France. All the setup was placed under the Cyberknife. After capturing a DNA bundle, SNT's tips are placed inside a microfluidic cavity; the alignment and the insertion are controlled by a micro-robot. Two different experiments in the same conditions are compared (two different bundles). For both bundles the resonant frequencies of the SNT decreases exponentially in the same proportion during the irradiation (total dose 30 Gy).
We also performed electromechanical detection of single stranded DNA (ssDNA) bundle generated on the tips of tweezers via isothermal rolling circle amplification (RCA) [24]. The DNA bundle generated between the tips of SNT was visually confirmed and detected by measuring electrical impedance and mechanical resonant frequency as well. The proposed approach may be used for pathogen detection by designing the proper primer sequence.
MEMS tweezers allow the manipulation of biological samples such as individual microtubules of 25 nm in diameter[25]. Hanging over a trench between parallel walls, the microtubules can be picked by sharp protruding tips. A motorized stage positions the SNT with high precision to place the microtubules carried between the tips. Repeating this pick-and-place cycle, a multilayered microtubule network is generated to define the motion of beads attached with kinesin in selected directions.

3.3. SILICON INCHWORM ACTUATOR

We also developed an inchworm actuator to enable micro-positioning applications for large displacements. A growing need for these actuators with low-voltage and low-power operation is observed for in vivo biomedical applications where one important design criterion is to cope with the limited available power. The actuator has an in-plane angular deflection conversion which provides a force-displacement tradeoff and allows to set step sizes varying from a few

[23] G. Perret, T. Lacornerie, F. Manca, S. Giordano, M. Kumemura, N. Lafitte, L. Jalabert, M.C. Tarhan, E. Lartigau, F Cleri, H. Fujita, D. Collard, "Real Time Mechanical Characterization of DNA Degradation under Therapeutic X-rays and its Theoretical Modeling," Microsystems & Nanoengineering, Vol. 2, Article no. 16062 (2016), doi:10.1038/micronano.2016.62

[24] S. L. Karsten, M. Kumemura, L. Jalabert, N. Lafitte, L. C. Kudo, D. Collard, et al., "Direct Electrical and Mechanical Characterization of In Situ Generated DNA between the Tips of Silicon Nanotweezers (SNT)," Lab on a Chip, vol. 16, pp. 2099-2107 (2016)

[25] M. C. Tarhan, R. Yokokawa, L. Jalabert, D. Collard, H. Fujita, "Single Molecule Manipulation: Pick- and-Place Assembly of Single Microtubules", Small, Vol. 13, (2017) DOI: 10.1002/smll.201770172

nanometers to a few micrometers with a minor change in design. Figure 2 illustrates the concept and the fabricated device.

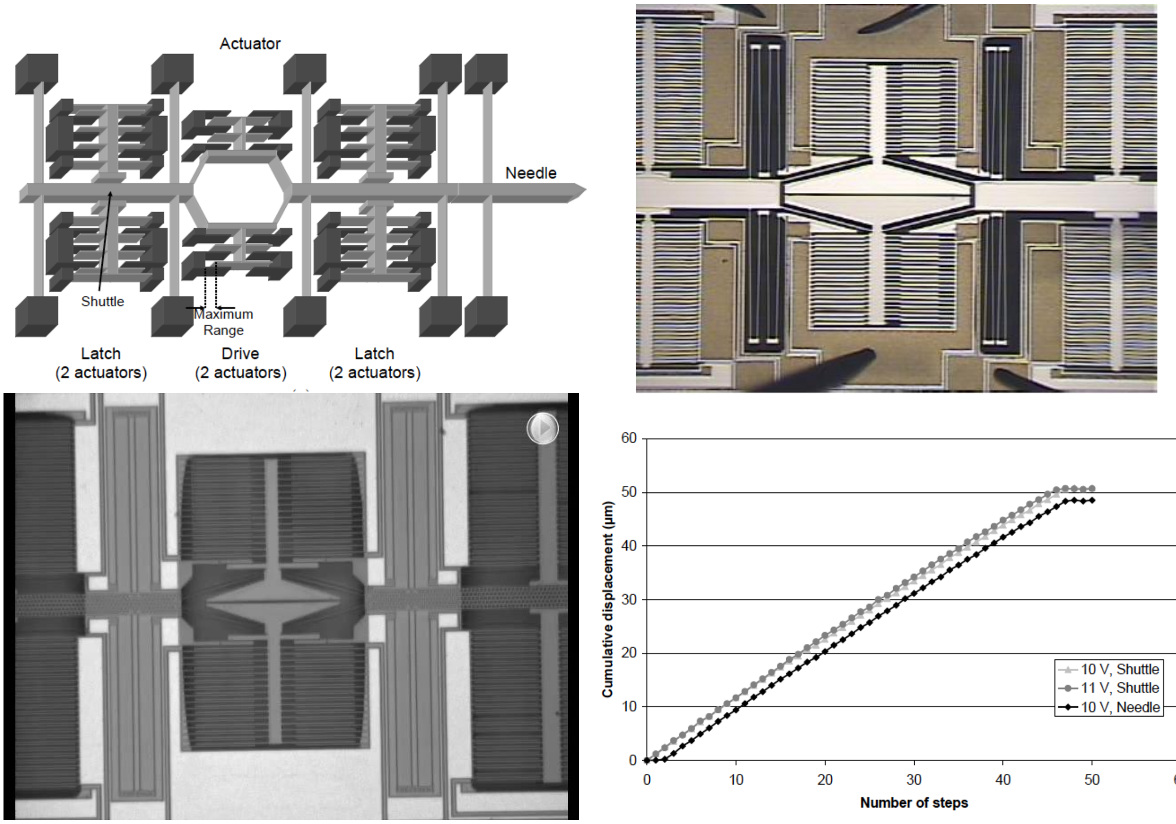


Figure 2 : Operation principle, optical and SEM picture and performance of the electrostatic inchworm actuator

This property not only allows possibility of designing different step size actuators for different applications, but also provides low-voltage and low-power operation. One actuator works at only 6 V and enables a range of ± 18 µm and ± 25 µN output force. An optimized actuator works with a slightly larger voltage (9 V) and can generate a 50 µm range and 0.3 mN output force. 0.4 mN output force actuators are also achieved with 12 V operating voltage[26]. The encapsulation is also very important. In vivo biomedical applications require water-tight packaging of the actuators. A successful encapsulation is achieved using a flip-chip technique with the help of rendering the surfaces hydrophobic. The packaging technique is demonstrated to allow the actuators to work in aqueous environments[27]. It is believed that this work brings several opportunities for future research and achieves a step in developing arrays of moving microneedles for health monitoring and patient treatment.

---

[26] M. Erismis, H. Neves, R. Puers, Ch. Van Hoof, "A low voltage, large displacement, large force inchworm actuator", IEEE JMEMS, J. Microelectromech. Syst., vol. 17, 2008, pp.1294-1301

[27] M. Erismis, H. Neves, P. De Moor, R. Puers, C. Van Hoof, "A water-tight packaging of MEMS electrostatic actuators for biomedical applications", Microsystem Technologies, Vol.16, 12, 2010, pp. 2109-2113

4. Piezoelectric actuators

Piezoelectric actuation offers also an interesting potential, especially at the micro- and nanometer scale. Piezoelectric crystals such as PZT, AlN or ZnO, when loaded in a specific direction, produce a charge. Reversely, they also generate force and expand when a voltage is applied. Typically, piezoelectric crystals only expand in the submicrometer range and high voltages need to be applied. To remedy the limited stroke, a wide range of mechanical configurations to increase the stroke of the actuators exists[28]. Now piezoelectric actuators have found a wide range of applications in areas such as ultrasonic transducers, micropumps[29], industrial inkjet printers, positioning systems with subnanometer accuracy[30], micromotors (e.g. in autofocus camera lenses)[31] and so on. The research on piezoelectric actuation is still widely continuing. An excellent example is the development of piezoelectric nanowires, which promises enhanced sensitivity, reduced actuator voltage and improved lifetime[32], especially if they are connected in an array. Non-typical uses of nanowire piezo's are now also coming within reach, such as power generation when woven into textiles[33].

A very promising application field for piezoelectric transducers is in ultrasound for sensing, actuation, short range data transfer and imaging. Piezoelectric micromachined ultrasound transducers (PMUTs), that consist of thin film membranes, coated with piezoelectric thin films, formed on silicon substrates, are a potential solution for integrated transducer arrays. In the last decades, ultrasound has found many industrial and medical applications, such as ultrasonic actuation [34], medical imaging [35].[36].[37].

---

[28] Dong, Shuxiang. "Review on piezoelectric, ultrasonic, and magnetoelectric actuators." *Journal of Advanced Dielectrics* 2.01 (2012): 1230001.

[29] Ma, Yu-ting, et al. "Resonantly driven piezoelectric micropump with PDMS check valves and compressible space." *Piezoelectricity, Acoustic Waves, and Device Applications (SPAWDA), 2014 Symposium on*. IEEE, 2014.

[30] Versteyhe, Mark, Dominiek Reynaerts, and Hendrik Van Brussel. "A rigid and accurate piezo-stepper based on smooth learning hybrid force-position controlled clamping." *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*. Vol. 4. IEEE, 1998.

[31] Guo, Mingsen, et al. "A small linear ultrasonic motor utilizing longitudinal and bending modes of a piezoelectric tube." *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on* 61.4 (2014): 705-709.

[32] Wang, Xudong, and Jian Shi. "Piezoelectric nanogenerators for self-powered nanodevices." *Piezoelectric Nanomaterials for Biomedical Applications*. Springer Berlin Heidelberg, 2012. 135-172.

[33] Chen, Xi, et al. "1.6 V nanogenerator for mechanical energy harvesting using PZT nanofibers." *Nano letters* 10.6 (2010): 2133-2137.

[34] Watson, B.; Friend, J.; Yeo, L. ,"Piezoelectric ultrasonic micro/milli-scale actuators". Sens. Actuators A Phys. 2009, 152, 219–233.

[35] Y. Chen, X. Ma, H. Huang, X. Li, and J. Yuan, "A 360 fully functional endoscopic ultrasound radial array,". in Ultrasonics Symposium (IUS),2016 IEEE International. IEEE, 2016, pp. 1–4.

[36] K. Chen, H.-S. Lee, and C. G. Sodini, "A column-row-parallel asic architecture for 3-d portable medical ultrasonic imaging,". IEEE Journal of Solid-State Circuits, vol. 51, no. 3, pp. 738–751, 2016.

The structure of a typical piezoelectric ultrasonic transducer is shown in Figure 3. It has a layer of piezoelectric material sandwiched by thin electrode layers, here Ti/Pt and an Al top electrode. [38]

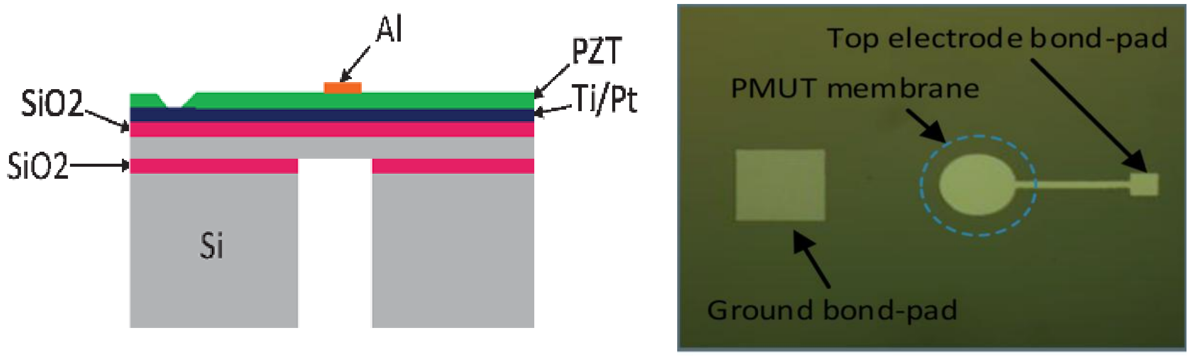


Figure 3. Typical cross-sectional structures and top view of piezoelectric ultrasonic transducer

The membranes of the PMUTs undergo flexural vibrations caused by the electrical AC excitation of a piezoelectric membrane. The piezoelectric effect introduces a lateral strain in the membrane, which in fact is a composite membrane of several layers. Often, one tries to make the silicon carrier dominant in determining the resonant frequency. Then, the flexural mode resonant frequencies depends on the membrane geometry, and is also influenced by intrinsic stress of the sandwich layers. PMUTs do not require a large actuation voltage, which makes them more adapt for a combination with CMOS low voltage circuitry.

Key is the optimization of the deposition of PZT thin-films. The sol-gel process is a preferred method, that allows good control of the crystal directivity. Typical resonance frequencies are ranging from several 10kHz up to a few MHz. Displacement of the membranes can run up to 1200 nm/V[18].

Figure 4 illustrates a nice optical device[39] that consists of a two-dimensional MEMS optical scanner. It is actuated by the piezoelectric effect of a thin film PZT. Scan range is ±12° at 25 kHz for the horizontal mode and ±8° at 60 Hz for the vertical mode, and the overall power consumption is 100 mW or less. A newly designed mechanical rib structure on the backside of the mirror was found to suppress the dynamic deformation of the mirror to the level compatible with a high definition of 720 pixels or more. A

scanning laser type pico-projector was developed for demonstration

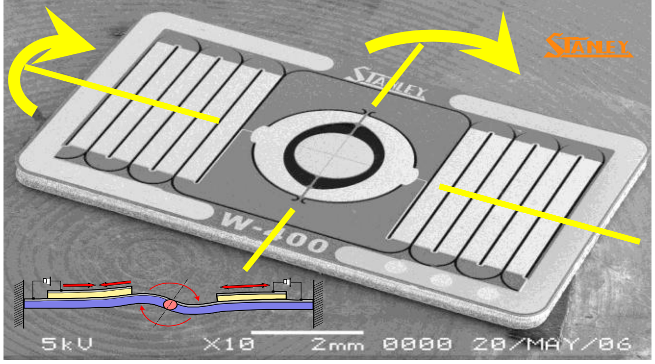
Figure 4. Piezoelectric driven scanning laser display

---

[37] D. Wildes, W. Lee, B. Haider, S. Cogan, K. Sundaresan, D. M. Mills,C. Yetter, P. H. Hart, C. R. Haun, M. Concepcion et al., “4-d ice: A 2-darray transducer with integrated asic in a 10-fr catheter for real-time 3-d intracardiac echocardiography,” IEEE transactions on ultrasonics, ferroelectrics, and frequency control, vol. 63, no. 12, pp. 2159–2173, 2016.

[38] S. Sadeghpour, R. Puers, “Optimization in the design and fabrication of a PZT piezoelectric micromachined ultrasound transducer (PMUT)”, MDPI Proceedings 2018, 2, 743, doi:10.3390/proceedings2130743.

[39] K. Ikegami,T. Koyama, T. Saito, Y. Yasuda, H.Toshiyoshi. " A biaxial piezoelectric MEMS scanning mirror and its application to pico-projectors." *Int. Conf. on Optical MEMS and Nanophotonics, 2014, pp.95-96*



5. Pneumatic, phase change and thermal actuators

The existing lithography tools can also yield small versions of classic pneumatic or hydraulic piston-cylinder actuators at the microscale: beneficial scaling laws dictate that both large strokes and large forces are obtainable from sub mm-size actuators. However, sealing and friction become the limiting factors[40], as well as the control valves to operate the actuators. Elastic actuators, e.g. relying on the inflation of a miniature bellow or balloon form a separate and interesting class in micro-hydraulic actuators[41].

If the necessary compressed fluid cannot be supplied from outside, there are several ways to generate it at the small scale: notable sources include methods include the melting of paraffin wax which tends to expand severely, heating a gas and evaporating a liquid. The latter method is used to eject ink droplets in almost all home inkjet printers, of which the high speed is only possible due to the favorable scaling of the time constant of heating a volume of liquid. Another method consists of reversible electrochemical reactions: for example, water can be split into hydrogen and oxygen in a miniature fuel cell, which can also be used to combine the gases produced back into water[42]. below.

Ionic Polymer Metal Composites (IPMC) are one of the more promising electrically actuated polymer materials[43].. They rely on the displacement of ions in a sheet of polymer induced by an electric field.

---

[40] De Volder, Michaël, et al. "A PDMS lipseal for hydraulic and pneumatic microactuators." *Journal of Micromechanics and microengineering* 17.7 (2007): 1232.

[41] Jo Choonghee et al. “Recent advances in ion polymer-metal composite actuators and their modeling and applications” *Progress in Polymer Science 38* (2013) 1037-1066..

[42] R Sheybani et al., “A MEMS electrochemical bellows actuator for fluid metering applications” *Biomedical Microdevices 15* (2013) 37-48.

[43] De Volder, Michaël, and Dominiek Reynaerts. "Pneumatic and hydraulic microactuators: a review." *Journal of Micromechanics and microengineering* 20.4 (2010): 043001.

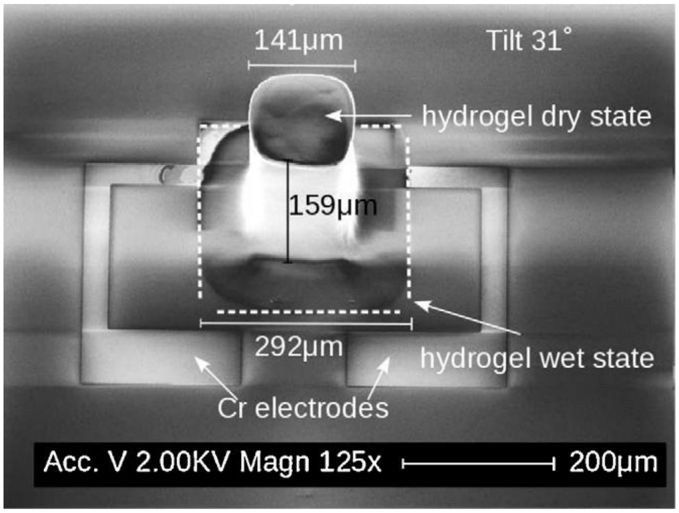


Figure 5: electrically sensitive hydrogel[44]

There are other ionic-movement based actuators, such as electrically sensitive hydrogels which can -albeit slowly- swell hundreds percent when exposed to an electric field (figure 5) and electrorheological fluids of which the viscosity can be modulated by an electric field. They do not require a high voltage, and their volume increase can be up to 400%.

Finally, pneumatically actuated artificial muscles such as the McKibben actuator are finding good use in miniature applications such as robotic hand prostheses[45] and have been downscaled to mm dimensions[46], but not below.

6. CONCLUSION

We have given a bird's eye view on the exiting and growing field of micromachined actuators. Many interesting developments have shown up over the last decade, and will continue to do so in the foreseeable future. We can distinguish several levels of developments. The first and most basic level is new material development. Especially in the 'smart material' research field, which encompasses i.a. the polymer actuators discussed above, one relies heavily on this and more innovation is bound to come. But further basic research is also taking place in more traditional solid state domains, such as piezomaterials. Of course the invention of novel actuation principles may not be ruled out as well.

A next level is the design of the actuators and their microfabrication processes. Novel designs and design methodologies such as evolutionary computing can without doubt improve existing technologies. Finally, the application level must be addressed. Most current commercially available MEMS devices are sensors, not actuators. Next to market forces, which are beyond

---

[44] Guan, Tiannan, et al. "Development and fabrication of a novel photopatternable electric responsive Pluronic hydrogel for MEMS applications." *Sensors and Actuators A: Physical* 186 (2012): 184-190.

[45] Schulz, Stefan, Christian Pylatiuk, and Georg Bretthauer. "A new ultralight anthropomorphic hand." *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*. Vol. 3. IEEE, 2001.

[46] De Volder, Michaël, A. J. M. Moers, and Dominiek Reynaerts. "Fabrication and control of miniature McKibben actuators." *Sensors and Actuators A: Physical*166.1 (2011): 111-116.

the scope of this article, we have mentioned several reasons already: the limited force often generated and the connection of the fragile internal structure of the device with the outside world. Therefore, most successful microactuators are targeting applications that require little force and allow to physically separate the actuator from the environment, e.g. in optical beam steering. However, this does not necessarily have to stay like this. It is, as often, instructive to look at nature for inspiring examples. One does not have to look far: a common muscle cell contains many thousands of 5 nm diameter actin fibres, acted upon by myosin molecules. They form a molecular linear motor, powered by the conversion of ATP to ADP. Muscle fibers can exert forces per area of up to 300 kPa, and contract about 30%[47],. Self-repair and self-assembly features come with the design, and the basic motor units combine well into small or large assemblies, tailored to the application.

At this point, it is impossible to predict how much our actuator technology will approach or even surpass nature in the far future. Nevertheless, we can safely cite Feynman once again: also for microactuators “there is plenty of room at the bottom”.

---

[47] Jean-Pierre Rospars et al., “Force per cross-sectional area from molecules to muscles: a general property of biological motors” *Royal Society open science 3* (2016)160313