

# A REVIEW ON ACTUATION PRINCIPLES FOR FEW CUBIC MILLIMETER SIZED MOBILE MICRO-ROBOTS

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## Abstract:

Actuation systems for few cubic millimeter sized mobile autonomous robots are subject to severe constraints in terms of e.g. size, fabrication or power consumption. Also the onboard electronics has limited performance due to both size and power restrictions, so actuation voltages, currents and frequency should be minimized.

Various principles of electrical to mechanical energy conversion will be presented (piezoelectric, polymer, electrostatic) and their performances compared considering the above mentioned constraints. For propulsion, a further mechanical to mechanical conversion is necessary to allow long strokes. We will compare four principles for this conversion: inertial drives, walking, inch-worm and propulsion based on asymmetrical friction forces.

Solutions where the energy is not onboard but rather scavenged in the environment are also reviewed. These solutions try to circumvent the energy limitations but present some inconveniences, especially when several micro-robots have to be simultaneously steered and/or propelled.

Keywords: micro-robotics, micro-actuators, propulsion, low power, energy, MEMS

## Introduction

This review doesn't pretend to cover all actuating principles possibly applicable to cubic millimeter sized mobile robots, but rather to propose an overview of the issues and problems that arise with miniaturization. A common way to address this topic is to compare actuators in terms of energy density through a scaling law analysis [1]. Such approach, although necessary in a first step, unfortunately does not address technological issues such as fabrication, packaging or complexity of the drivers, issues that are the dominant parameters to select an actuating principle. T. Ebefors and G. Stemme also present an interesting review on micro-robotics actuation and fabrication [2]. In the present paper, the authors address miniaturization issues more from a practical point of view taking into account the constraints imposed by mobile autonomous micro-robotics and based on their experience acquired in several projects such as MINIMAN, MiCRoN or I-SWARM [3-5].

Although very exciting works are nowadays addressing swimming or flying micro-robots, we limit this review to propulsion systems for locomotion purposes on smooth, horizontal surfaces. This review will not address either the fascinating bottom up approach where the robots are built out of biological components such a bacteria or even muscles [6].

First we give a short overview of solutions proposed to circumvent the main challenges of miniaturization by external propulsion and steering of the robots. Then we describe the basic components present in all autonomous micro-robots.

Two energy transformations characterize the actuators: the electrical to mechanical transformation and the mechanical to mechanical transformation that will generally amplify the actuator strain. Piezoelectric, polymer and electrostatic actuators are the most used principles for the electrical to mechanical transformation. The mechanical to mechanical transformation is often obtained with inertial drives, walking mechanisms, inch-worm or actuators with asymmetrical friction forces. They are explained and illustrated with a few examples.

## Remote propulsion and steering

Solutions where the energy is not onboard but rather scavenged in the environment have been proposed in literature. These solutions try to circumvent the onboard energy limitations but present some inconveniences, especially when several micro-robots have to be propelled and steered simultaneously and independently.

Yasuda et al. proposed to supply the power to the robots through a mechanical vibration of the working floor [7]. The robots, whose legs vibrate at different resonance frequencies, are individually steered by selecting the appropriate frequency. The authors claim velocities up to 2 mm/s for 3 degrees of freedom micro-robots. The robots, 1.5 x 0.7 mm<sup>2</sup>, are micro fabricated in polysilicon and polyimide. Although the principle is attractive, the possibility to accurately steer several robots on the same floor are very limited.

Martel et al. [8] have demonstrated that it is possible to propel and steer a micro-device in a human blood circulatory system using the strong magnetic field of a Magnetic Resonance Imaging (MRI) instrument.

Similarly, Nelson et al. [9] are investigating the limit and potential of such system for drug delivery, cell separation or protein manipulation. Both papers show the great potential of such approach, but also emphasis on the challenges. When scaling down, extremely high magnetic field gradients are necessary and the micro-fabrication of good quality hard magnetic materials is still a problem.

Donald et al. [10] proposed to deliver the power to the robots via capacitive coupling and suggested a fabrication process allowing for batch fabrication. Several robots actuated by scratch drives type actuators (SDA) can be powered at a velocity up to 1.5 mm/s. Future works propose to achieve independent steerable locomotion.

To conclude this brief overview we can mention the photostrictive ferroics materials where a strain is induced by illumination. Various systems have been proposed based on this principle, one of them consisting on two photostrictive bimorphs ( $5 \times 20 \times 0.35 \text{ mm}^3$ ) [11].

Among these solutions the powering through electromagnetic and electrostatic fields offers a major potential and so far the only realistic way to miniaturize the robots below the cubic millimeter size. However, for micro-robots of a few  $\text{mm}^3$ , real autonomous operation becomes feasible and will be discussed in the rest of this review.

### **Micro-robot structure**

Surprisingly, in literature only a few papers address all the aspects of autonomous micro-robots. Apart from a few exceptions [4, 12] publications concentrate mainly on the sensors and the actuators, and in general the fabrication issues are well addressed but often the proposed solutions are not applicable in really autonomous micro-robots due to lack of adequate electrical signals (low voltage and current, digital signal, ...). Hence, we briefly describe the structure of a micro-robot and its inherent limitations in terms of powering and onboard electronics.

All autonomous micro-robots are composed of 4 main modules:

#### *Energy module:*

The energy is probably the most challenging problem of micro-robotics in general. It can be scavenged from the environment e.g. by electromagnetic coupling [4, 13] micro-vibration or photo voltaic modules. In the millimeter size, only the last solution can be considered [12]. An interesting technology is the thin-film amorphous silicon (a-Si:H) [14] that offers a high efficiency (25%) for indoor applications. Under a good illumination (cold illumination spectrum), a micro-robot with an active surface of  $10 \text{ mm}^2$  can scavenge up to 1 mW [15]. A voltage of a few tens of volts is

feasible by connecting several segments in series [12]. More segments mean also more interconnections hence a reduction of the active surface. A realistic compromise seems to be in the range of 10 to 20V.

The energy must also be stored on board. Cymbet corporation [16] have demonstrated thin film Li-batteries technologies with up to  $8 \mu\text{Ah}/\text{mm}^2$  (typical thickness 5 to 20  $\mu\text{m}$ ) resulting into an autonomy of a few minutes for a power consumption of 0.5 mW. However, it is still unclear if a Li-battery can be downsized as much as a few square millimeters.

It is important to note that a complex system such as an autonomous robot requires various voltages that make the power management relatively complex. Due to technology constraints, compromises that are not necessarily optimal in terms of efficiency have to be accepted.

#### *Communication module:*

If the robots have to accomplish some real tasks, it is compulsory to equip them with a communication system. Due to the small size of the robots, and therefore of the antenna (a few millimeters), radio frequency in the GHz range is not applicable.

In the Smart Dust project [17], infrared (IR) communication with reflective corner cube mirrors is proposed. In addition to IR, I-SWARM partners have demonstrated that inductive coupling communication is feasible. In both cases, the communication range is very short (a few millimeters) due to the very limited on-board energy.

#### *Onboard electronic module:*

The onboard electronics is the heart of the robot. It includes the peripherics (inputs for the sensors and drivers for the actuators, ...) and possibly some computing power. Nowadays, it is possible to integrate in a very small area (typically  $4 \text{ mm}^2$ ) a complete micro-processor with its peripherics. However, the main problem remains, i.e. the energy consumption. As the size shrinks, the leakage currents become predominant. In order to minimize the power consumption the operating voltage must be as low as possible (e.g. 1.2 V) and peripherics such as digital to analog converter should be avoided. In I-SWARM [5] robots the onboard electronics is expected to consume a power in the range of  $500 \mu\text{W}$ .

#### *Sensors and actuators module:*

Sensors and actuators must be selected and designed considering the constraints described above. In summary:

*Power:* a few tens of  $\mu\text{W}$ ;

*Voltage:* a few tens of volts;

*Driving signals:* ideally purely digital

With these values in mind we are now going to present a few solutions applicable for onboard actuators and more specifically for the propulsion of the micro-robots.

### Electrical to mechanical energy conversion

Although many possibilities exist to convert electrical energy into mechanical energy, this review addresses only the main three principles that are the most suitable for miniaturization through micro-fabrication techniques, namely: piezoelectric, polymer, and electrostatic actuators.

### Piezoelectric actuators

Piezoelectric actuators are materials with a specific crystal structure that develop an electric charge when subjected to mechanical stress (direct effect) and that develop a mechanical strain when subjected to an electrical field (converse effect) [18]. The most used group of materials for piezoelectric actuators is PZT ( $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$ ). Within this group a difference can be made between hard PZT (typically good mechanical quality factor) and soft PZT (typically larger strains). Depending on the orientation of the polarization field  $P$  and the actuation field  $E$  and the exploited displacement three different actuation modes of the actuators can be distinguished: axial, transversal and shear mode (Fig. 1). In the case of axial and transversal mode, the actuation field is applied parallel (either in the same sense or in the opposite sense) to the polarization field, resulting into an axial deformation ( $\delta_t$ ) and a transversal deformation ( $\delta_l$ ). When the actuation field is applied perpendicular to the polarization field, a shear strain ( $\delta_s$ ) is induced. Table 1 gives an overview of the formula for free strain, blocking force and capacitance of piezoelectric actuators for the different actuation modes. Typical values for coupling coefficients in the case of PZT are  $d_{33}=300\dots800\times10^{-12}\text{m/V}$ ,  $d_{31}=-150\dots-350\times10^{-12}\text{m/V}$ ,  $d_{15}=400\dots900\times10^{-12}\text{m/V}$ . Typical values for the elastic constants are  $s_{33}=12\dots23\times10^{-12}\text{m}^2/\text{V}$ ,  $s_{11}=11\dots17\times10^{-12}\text{m}^2/\text{V}$  and  $s_{55}=38\dots48\times10^{-12}\text{m}^2/\text{V}$ . Relative permittivity constants are in the range of  $\epsilon_{33}=1500\dots5500$  and  $\epsilon_{11}=1400\dots4500$ . Piezoelectric actuators feature a relatively low strain for high driving voltages, but a relatively high blocking force and bandwidth. The resulting energy density is rather high and the mechanical strain can be increased by a mechanical amplification. The most commonly used amplification mechanisms are multi layer actuators and bending actuators [18]. In terms of electrical behavior a piezoelectric actuator can be approximated by a capacitance when actuated sufficiently below its first resonance frequency. Hence, the power consumption of a piezoelectric actuator is given by  $P = \frac{1}{2} fCV^2$ , in which  $f$  is the actuation frequency. More efficient operation and

higher mechanical strains can be obtained when working in resonance mode.

Piezoelectric actuators are commonly used for locomotion and actuation of mobile micro robots of a size between  $1\text{ dm}^3$  and  $1\text{ cm}^3$ . They are integrated on the robot in the shape of multi layer stack actuators [19], single or multi layer 1 DOF bending actuators [20, 21], single or multi layer 2 DOF bending actuators [22, 23] and monolithic bulk actuators with electrode structuring [24]. However, all these designs and the used fabrication techniques are difficult to scale down for robots smaller than  $1\text{ cm}^3$ . On the other hand several high resolution micro fabrication techniques for thick and thin film printing of piezoelectric layers exist [25], but no piezoelectric micro robot of a size of some  $\text{mm}^3$  has been reported yet.

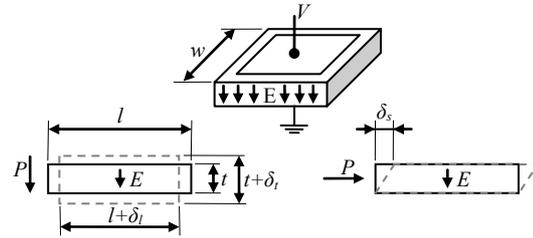


Fig. 1: Actuation modes of piezoelectric actuators.

Table 1: Free strain, blocking force and capacitance for the 3 piezoelectric actuation modes.

	Axial	Transversal	Shear
Free strain	$\delta_t = d_{33}V$	$\delta_l = d_{31}\frac{t}{l}V$	$\delta_s = d_{15}V$
Blocking force	$F_b = \frac{d_{33}}{s_{33}}\frac{wl}{t}V$	$F_b = \frac{d_{31}}{s_{11}}wV$	$F_b = \frac{d_{15}}{s_{55}}\frac{wl}{t}V$
Capacitance	$C = \epsilon_0\epsilon_{33}V\frac{wl}{t}$	$C = \epsilon_0\epsilon_{33}V\frac{wl}{t}$	$C = \epsilon_0\epsilon_{11}V\frac{wl}{t}$

### Polymer actuators

There are several electroactive polymers (EAP) considered for microsystems and micro-robotics. One reason for this is that polymers are more easily processed and miniaturized than the aforementioned piezoelectric actuators.

Both dry and wet EAP's have been evaluated in micro-robotics type of applications and their respective advantages and disadvantages have been demonstrated, e.g. [26-29]. The main dry polymer EAP's are the PVDF-based (poly-vinylidene fluoride) ferroelectric materials and the dielectric elastomers, while the most investigated wet polymers are the Ionic Polymer Metal Composites (IPMC) and the conducting polymers. In Table 2 four selected EAP materials are presented with typical data at ideal conditions.

Several modifications of ferroelectric polymers based on the PVDF and especially of its copolymer

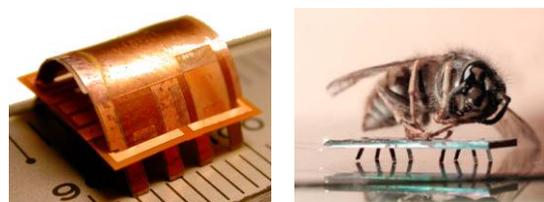
with trifluoroethylene, P(VDF-TrFE) have been explored during the last decade. Basically, the copolymer generates piezoelectric strains when subjected to an electrical field, but much more promising performance has been obtained when structural defects are created by high energy irradiation or chemically by introduction of a third monomer into the copolymer. Thereby, electrostrictive behavior with high stresses and strains has been demonstrated. The terpolymer P(VDF-TrFE-CFE) where CFE is chloro-fluoroethylene, has so far demonstrated the best properties [30]. A coupling coefficient of 0.55 has been measured at high electrical fields, indicating that a high efficiency could be possible. The Young's modulus is about 1 GPa and maximum strain and stress are 4 % and 50 MPa respectively. The ferroelectric EAP's can be fabricated with several techniques and by spin-casting the actuators can be made as a multilayer (with intermediate electrodes) to reduce the drive voltages to levels suitable for autonomous robot applications [31]. A design example of a locomotion module based on a flexible printed circuit board carrier with 8 P(VDF-TrFE) actuated legs is shown in Fig. 2. While the electrostrictive materials operate well into the ultrasonic region, the piezoelectric copolymer P(VDF-TrFE) can be used in the ten MHz region [32].

The use of elastomers as miniaturised actuators was first investigated by Pelrine et. al. [33]. The actuator consists of an elastomer film with electrodes coated on each side. When a voltage difference is applied between the electrodes, charges will accumulate in the electrodes whereby electrostatic attraction results in a longitudinal compressive stress that reduces the thickness of the film. The low Young's modulus of these materials makes it extremely important to use thin and compliant electrodes as e.g. grease and powders. With a pretension of the film it is possible to achieve more than 100% strain. The stresses will be relatively low due to the low Young's modulus. Repulsive charges in the compliant electrodes will also cause substantial transverse strain components (doubles the effect). The most critical issue regarding the elastomer actuator is the possibility to reduce the voltage since the electric field has to be in the 100 V/ $\mu\text{m}$  range to reach the exceptional performance. One solution would be an increase of the permittivity and another to make thin layers with intermediate electrodes. Both these routes involve great challenges.

The mechanisms for the dimensional change in conductive polymers are believed to be mainly related to swelling of the polymer during doping or undoping. Conformational changes of the backbone may also play a role. The polymer is normally in

contact with an electrolyte and there will be an ion transport in or out of the conducting polymer. The voltage necessary for this ion transport is low, typically in the order of few volts, which is one of the great advantages of these types of actuators. The shape change of the conducting polymers is typically a few % which is sufficient in many applications. The closed network of the conducting polymers results in a high mechanical strength and actuation stresses of up to 35 MPa have been reported [34]. The dense network in combination with the necessity to move larger dopant ions make the response time slow. A typical cycle time for a 1  $\mu\text{m}$  thin film is about 1 s. Some examples of polymers that have been studied are: polyaniline, polyacetylene and polypyrrole.

The polymer actuators based on thermal expansion and phase-transformations, even though not electroactive, should also be included in a comparison of actuators for these types of microsystems, Table 2. Large deflections can be achieved with external or internal leverage and devices based on Si V-grooves filled with polyimide [35] have demonstrated to yield both large deflections and high forces. Dynamic measurements resulted in bending angles  $>5^\circ$  for temperature differences of some hundred K and the cut-off frequency was in the range 1-10 Hz. The polyimide used is patterned lithographically, i.e. prepared for batch fabrication, and has good properties for this actuator application. The coefficient of thermal expansion is approximately 50 ppm/K, the Young's modulus about 2-3 GPa and the material can withstand temperatures well above 400  $^\circ\text{C}$  giving maximum strains and stresses of about 2% and 40 MPa. Polyimides in general have good mechanical properties with yield stresses above 100 MPa. The disadvantage with thermal expansion is that the efficiency can never be better than about 1% but on the other hand in many cases it is rather the power consumption that is the important parameter since the robots typically do not perform any work.



**Fig. 2:** Left: Miniature robot based on two flexible printed circuits with 8 PVDF actuated legs, Uppsala University (UU). Right: A silicon microrobot based on thermally actuated polyimide V-grooves (courtesy of T. Ebefors and J. U. Mattson, Royal Institute of Technology, Stockholm).

**Table 2: Performance of some interesting polymer materials for microsystems and microrobotics.**

Polymer act. materials	Dielectric elastomer	Conduct. polymers	Ferroel. polymers	Polyimide thermal
Strain max. (no creep) [%]	>100	~2	~4	~4
Stress max.* [MPa]	~1	~5	>20	~40
Energy density max. [J/kg]	~1.000	>100	~1.000	>100
Strain rate max [%/s]	>10.000	~10	>10.000	~100
Cycle life	~10 <sup>6</sup>	~10 <sup>6</sup>	--	>10 <sup>8</sup>
Efficiency max	medium	low	medium	low
Temp. range (-40 ... +70 °C)	full range	limited	limited	full range
Drive voltage [V]	kV	few volts	kV	few volts
Tech. maturity, miniature scale	medium	low	low	high

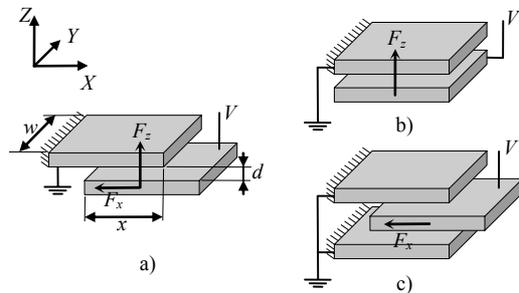
### Electrostatic actuator

In accordance to the principle of virtual work, the force between two conductive plates with a potential difference  $V$  is given by the derivation of the energy  $U = \frac{1}{2}CV^2$  in  $X$  and  $Z$  directions:

$$F_x = \frac{\partial U}{\partial x} = \frac{1}{2} \epsilon_0 \epsilon_r \frac{w}{d} V^2$$

$$F_z = \frac{\partial U}{\partial z} = \frac{\partial U}{\partial d} = -\frac{1}{2} \epsilon_0 \epsilon_r \frac{xw}{d^2} V^2$$

with usually  $\epsilon_r = 1$  for air or vacuum environment.

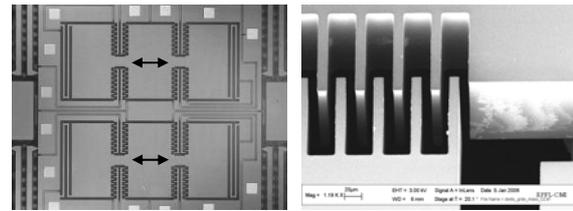


**Fig. 3: Perpendicular ( $F_z$ ) and lateral force ( $F_x$ ) on an electrostatic actuator.**

Usually, electrostatic actuators are designed to exploit either the perpendicular force  $F_z$  (Fig. 3b) either the lateral force  $F_x$  (Fig. 3c). In order to increase the actuation force a large number of the elementary actuators depicted in Fig. 3 are put in parallel resulting into interdigitated comb structures. The most commonly used design is a comb structure of equally-spaced fingers resulting into a purely lateral force [36]. This design has the advantage of a linear behavior in the actuation direction ( $X$ ), the possibility of large displacements (up to 150  $\mu\text{m}$ ) and a very good mechanical quality factor due to low internal damping of actuator material (usually Si) and the lack of squeeze film air damping. Comb-drive electrostatic actuators can have resonance

frequencies ranging from a few hundreds of Hz to several tens of kHz. Power consumption is typically very low as the involved capacitances are very low as well (max. some tens pF). On the other hand, the energy density is also relatively low compared to piezoelectric and polymer actuators: actuation forces are small and for large displacements high actuation voltages are required. However, one of the major advantages of comb-drive electrostatic actuators is their aptitude to miniaturization thanks to well-mastered high-aspect ratio fabrication technologies such as Deep Reactive Ion Etching [37]. It is the latter advantage that makes from electrostatic actuators the most commonly used MEMS actuator for in-plane displacements.

Fig. 4 shows a locomotion module based on the friction drive concept [38], consisting of two vibrating masses that are actuated by comb drive actuators fabricated in SOI by DRIE at EPFL. Obtained performances are an amplitude of 32  $\mu\text{m}_{\text{p2p}}$  at resonance frequency (419.2 Hz, quality factor  $Q=508$ ) for an actuation voltage of 16  $V_{\text{p2p}}$ .



**Fig. 4: Locomotion module ( $2 \times 2 \text{ mm}^2$ ) with two electrostatic actuated vibrating masses and SEM close-up on comb drive fingers (gap=11  $\mu\text{m}$ ).**

Electrostatic actuators are not only used as displacement actuators but also as clamping actuators. The actuator then corresponds to the configuration depicted in Fig. 3b, with typically between the two plates a dielectric with a high relative permittivity. MEMS fabrication technologies allow for very small (submicron) thicknesses of this dielectric layer, resulting into increased clamping forces.

An electrostatic inchworm motor with electrostatic clamping force has been reported in [39]. The electrostatic clamping force is also used in the Scratch Drive Actuator in order to produce an electrostatic stepping motor [10].

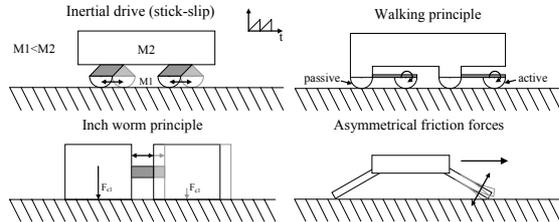
### Mechanical to mechanical energy conversion

Locomotion principles for micro-robots are based on some kind of stepping mechanism that allows for large motion ranges with small actuator amplitudes. The different stepping principles for these drives are summarized in Fig. 5.

### Inertial drive

The inertial drive principle is based on the strongly asymmetric vibration of contact feet (stick-slip) or

an inertial mass (impact drive) (Fig. 5). Both systems allow very high resolution but suffer from the fact that they need a driver with high performance in terms voltage slew rate which is not well adapted for miniaturization ( $< 1\text{cm}^3$ ).

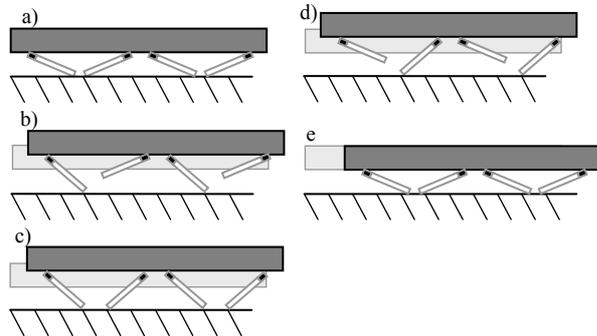


**Fig. 5:** Working principle of inertial drive (stick-slip), walking, inch worm, and asymmetrical friction forces locomotion principles.

Driesen et al. [38] propose a locomotion concept based on the superposition of a variation of the contact force between robot and work floor and a horizontal vibration generating a periodic slip at the interface between robot and work floor. This concept is very attractive for miniaturization as resonance mode operation is possible and moreover permitting various configurations where the energy can also be transmitted through a vibrating floor.

### Walking principles

The walking mechanism is often based on legs that create motion similar to the walking of biological species. The most important difference from e.g. stick-slip mechanisms is that it is possible to get good control also during the “step-over”, i.e. when one step is finished and the next is initiated. This is typically accomplished by using an overlap of the motion patterns of the different legs. It is hence feasible to get a continuous motion with almost constant velocity. A quasi static stepping motion is accomplished with legs that have only one degree of freedom as described in Fig. 6.



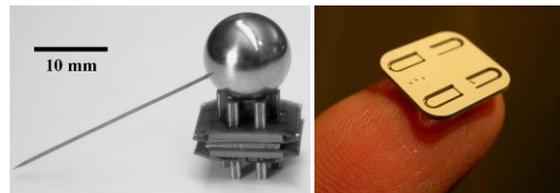
**Fig. 6:** The principle for quasi-static walking motion [2] with ciliary actuators.

It has been shown that when the normal force is reduced the mechanisms using a vertical motion component, which is necessary in the walking case, are sensitive to induced vibrations [40]. A walking

microrobot as the one developed in the EU-project MINIMAN, Fig. 7, [3] will be particularly sensitive since there are no external normal forces and the inertial force is very low. To avoid the bouncing in the vertical direction, which decreases motion control, the legs should have a low stiffness and one design solution is to have the legs in parallel with the surface to walk on, Fig. 18. This design was evaluated in the EU-project MiCRoN, [4] and preliminary results indicated that the leg bouncing is avoided in this case. The same leg design was used for rotation of the manipulator arm of the MiCRoN robot [20].

The walking actuators presented here have been manufactured with a modified thick-film technique for piezoceramic multilayer components [41], which makes it possible to mass-fabricate in analogy with fabrication of ceramic capacitors. The voltage limitation in microrobotics is an extremely important issue and a multilayer thickness adapted for typical voltage levels of about 50 V (compatible with standard IC technology) has been used but can readily be reduced to allow for drive voltages of 10-20 V without loss of performance. The difficulty in scaling down piezoceramic legs for a robot with a size of a few  $\text{mm}^3$  can be solved by replacing the actuator material with multilayer ferroelectric polymers.

The micro-robot presented in [12] is also a walking mechanism with two legs powered by electrostatic actuators. In spite of its complexity, it is remarkable to note that, to our knowledge, it is the only robot of this size that has been able to move a few centimetres in a totally autonomous way.



**Fig. 7:** left: Walking microrobot developed in the MINiMAN project. Right: A thin piezoceramic carrier with four multilayered piezoceramic legs (Courtesy of N. Snis, Uppsala University).

### Inch worm

The inch worm principle is based on the relative motion of two clamping units that are alternatively activated. Aoyama [19] proposes an electromagnetic clamping while Elenspoek et al. are developing very innovative inch-worms fully powered by electrostatics actuators, well adapted to miniaturization and batch processes [39].

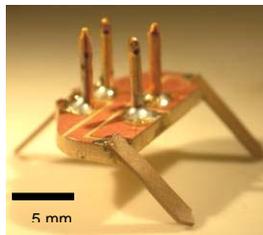
Compared to the other driving principles, the inch worm presents a higher driving force (due to clamping) and a quasi static operation. On the other hand, it is relatively complex (at least three phases)

and doesn't allow operation at resonance frequency. Finally, it is difficult to design an inch worm with several degrees-of-freedom.

### Asymmetrical friction forces

Some locomotion principles rely on a contact geometry that presents asymmetrical friction forces. The scratch drives actuators (SDA) are based on this principle. SDA can easily be batch fabricated by conventional micro-fabrication processes and offer interesting performances [10].

Other possibility is to use inclined cantilevers for the legs (Fig. 5). Exciting the legs at their natural frequency, they will vibrate and therefore induce a motion in the direction where the friction force is the highest. Due to its similarity to the mechanism of the biological cilia, such principle is known as ciliary actuator.



**Fig. 8:** A miniature locomotion module with piezoceramic cantilever legs operating in resonance (Courtesy of Niklas Snis, Uppsala University).

One of the great advantages with this mechanism is that very simple actuator elements can be used. Further it is well compatible with batch-processing [32] and several actuator materials can be used, e.g. [27]. However, to have a good controllability of the system the vibration must be perfectly controlled and that means high challenges for the mechanical and controller design. The main issues to be addressed are:

- achieving a suitable mechanical amplification (Q-value) – not too small but not too large to avoid the associated frequency sensitivity
- avoiding interfering resonances in the legs and/or mechanical structure
- finding the optimum mechanical properties of the interacting components, e.g. friction and stiffness

An example of a resonant ciliary type of motion is given in Fig. 8. The locomotion module is used in laboratory work at Uppsala University to study movement patterns when the legs are activated at various frequencies.

### Conclusion

In this paper we addressed the problems related to the design of actuators for a few cubic millimeter sized autonomous robots. We have seen that the micro-robot has to be considered as a whole system in order to take into account all the constraints

related to the miniaturization. Apart the fabrication and assembly issue, the limited performances of the onboard electronics in terms of power, voltages and computational power have to be taken into account to design actuators that will perform well in such small robots.

In spite of the remarkable progress achieved in the MEMS technologies, it is interesting to note that a really operating miniature autonomous robot has not yet been constructed. We believe that the technologies to achieve such goal exist; however, the complexity of the micro-robots requires competences in many fields and such research projects requires huge investments with not well defined return on investments. Fortunately, EU funded projects such as MiCRoN and I-SWARM are addressing these topics and will make it possible in a not too far perspective to built micro-robots which will be really capable to accomplish tasks.

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### References

- [1] R. S. Fearing, "Powering 3 Dimensional Microrobots: Power Density Limitations", in *IEEE Int. Conf. Robotics and Automation-Tutorial on Micro Mechatronics and Micro Robotics*, 1998.
- [2] M. Gad-el-Hak, "The MEMS Handbook", CRC Taylor & Francis, Boca Raton, 2006, vol. 2, chap. 7.
- [3] <http://i60p4.ira.uka.de/~seyfried/tikiwiki-1.7.3/tiki-index.php?page=MINIMAN>.
- [4] <http://i60p4.ira.uka.de/~seyfried/tikiwiki-1.7.3/tiki-index.php?page=MiCRoN>.
- [5] <http://i60p4.ira.uka.de/~seyfried/tikiwiki-1.7.3/tiki-index.php?page=I-Swarm>.
- [6] A. Ananthaswamy, "First robot moved by muscle power", *New Scientist* 181(2436), 2004, pp. 23.
- [7] T. Yasuda, et al., "Microrobot locomotion in a mechanical vibration field", in *Advanced Robotics*, Vol.9, No.2, pp 165-176 (1995).
- [8] S. Martel, et al., "Adapting MRI Systems to Propel and Guide Microdevices in the Human Blood Circulatory System", in *Proceedings of the 26<sup>th</sup> Annual International Conference of the IEEE EMBS*, San Francisco, 2004.
- [9] B. J. Nelson, et al., "Analysis and Design of Wireless Magnetically Guided Microrobots in Body Fluids", in *Proceedings of the 2004 IEEE International Conference on Robotics & Automation*, New Orleans, 2004.
- [10] B.R. Donald, et al., "Power Delivery and Locomotion of Untethered Microactuators", in

- Journal of Microelectromechanical Systems, Vol.12, No. 6, December 2003.
- [11] K. Uchino (1989) *J Rob Mech* 1(2), pp 124
- [12] S. Hollar, et al., "Solar Powered 10mg Silicon Robot", in *MEMS 2004*, Kyoto, Japan, January 19–23, 2004.
- [13] H. Nishikawa, et al., "In-Pipe Wireless Micro Locomotive System", in *International Symposium on Micromechatronics and Human Science* (1999).
- [14] J. Meier, et al., "Potential of amorphous and microcrystalline silicon solar cells", *Thin Solid Films*, Vol. 451-452, pp. 581-524, 2004.
- [15] A. Boletis, et al., "Solar Powering with Integrated Global Positioning System for mm<sup>3</sup> Size Robots", (to be published in *IROS* 2006).
- [16] <http://www.cymbet.com/highlights.php>.
- [17] B. Warneke, B. Liebowitz, K.S.J. Pister, "Smart Dust: Communicating with a Cubic-Millimeter Computer", *Computer* 34 (1), 2001, pp. 44-51.
- [18] K. Uchino, "Piezoelectric actuators and Ultrasonic Motors", Kluwer Academic Publishers, Bosten, Dordrecht, London, 1997.
- [19] H. Aoyama, O. Fuchiwaki and D. Misaki, "Piezo Based Micro Robots System for Precise Micro Bio- and Chemical Application," 9th Int. Conf. on New Actuators (Actuator 2004), pp. 164-167, Bremen, Germany, 2004.
- [20] N. Snis, U. Simu and S. Johansson, "A Piezoelectric Disc-shaped Motor using a Quasi-static Walking Mechanism", *J. Micromech. Microeng.* 15 (2005) 2230-2234.
- [21] W. Driesen, T. Varidel, A. Bergander, and J.-M. Breguet, "Energy Consumption of Piezoelectric Actuators for Inertial Drives", *IEEE Int. Symp. on Micromechatronics and Human Science (MHS 2003)*, Nagoya, 2003, pp. 51-58.
- [22] U. Simu and S. Johansson, "Evaluation of a monolithic piezoelectric drive unit for a miniature robot", *Sensors and Actuators A101* (2002) 175-84.
- [23] S. Martel et al., "Three-legged wireless miniature robots for mass-scale operations at the sub-atomic scale," *IEEE Int. Conf. on Robotics and Automation*, Proceedings, vol. 4, pp 3423-3428, 2001.
- [24] A. Bergander, W. Driesen, T. Varidel, and J.-M. Breguet, "Monolithic Piezoelectric Push-pull Actuators for Inertial Drives", *IEEE Int. Symp. on Micromechatronics and Human Science (MHS 2003)*, Nagoya, 2003, pp. 309-316.
- [25] T. Morita, "Miniature piezoelectric motors", *Sensors and Actuators, A: Physical* 103 (3), 2003, pp. 291-300.
- [26] T. Hayashi, S. Hoshi, "Research on micro-mechanism", *Proc. of the Sixth World Congress on the Theory of Machines and Mechanisms*, New Delhi, India (1983) 1045-1048.
- [27] E. Jager, E. Smela, O. Inganäs, "Microfabricating Conjugated Polymer", *Actuators, Science* 290 (2000) 1540-1545.
- [28] K. Jung, J. Nam, Y. Lee, H. Choi, "Micro Inchworm Robot Actuated by Artificial Muscle Actuator based on Non-prestrained Dielectric Elastomer", *Proc. of SPIE* 5385 (2004) 357-367.
- [29] B. Kim, J. Ryu, Y. Jeong, Y. Tak, B. Kim, J.-O. Park, "A Ciliary Based 8-Legged Walking Micro Robot using Cast IPMC Actuators", *Proc. of the IEEE Int. Conf. on Robotics & Automation Taipei, Taiwan* (2003) 2940-2945.
- [30] H. Li, F. Xia, H. Xu, D. Olson, C. Huang, Z.-Y. Cheng, Q.M. Zhang, G.J. Kavarnos, "Electromechanical properties and molecular conformation in P(VDF-TrFE) based terpolymer", *Proc. of SPIE* 4695 (2002) 167-175.
- [31] N. Snis, E. Edqvist, U. Simu, S. Johansson, "Resonant Multilayered P(VDF-TrFE) Actuators for Swarming Robots", *Proc. of 10th Int. Conf. on New Actuators (Actuator 2006)*, Bremen, Germany, 2006.
- [32] T. Blom, T. Lilliehorn, U. Simu, S. Johansson, M. Nilsson, M. Almqvist, "Multilayer piezoelectric copolymer transducers", *Proc. of 2005 IEEE Ultrasonics Symposium* 3 (2005) 1618 – 1620.
- [33] R.E. Pelrine, R.D. Kornbluh, J.P. Joseph, "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation", *Sensors and Actuators A64* (1998) 77-85.
- [34] J.D. Madden, R. Cush, T. Kanigan, I. Hunter, "Fast contracting polypyrrole actuators", *Synthetic Metals* 113 (2000) 185-192.
- [35] T. Ebefors, J.U. Mattsson, E. Kälvesten, G. Stemme, "A robust micro conveyor realized by arrayed polyimide joint actuators", *J. Micromech. Microeng.* 10 (2000) 337–349.
- [36] W.C. Tang, T.-C.H. Nguyen and R.T. Howe, "Laterally driven polysilicon resonant microstructures", *Sensors and Actuators*, 20, 1989 pp. 25-32.
- [37] Gomez, S., et al., "Etching of high aspect ratio structures in Si using SF<sub>6</sub>/O<sub>2</sub> plasma", *J. of Vacuum Science and Technology A*, 22(3), 2004, pp. 606-615.
- [38] W. Driesen, J.-M. Breguet, R. Clavel, "Novel locomotion principle for mobile micro robots", *Int. Conf. on New Actuators (Actuator 2006)*, Bremen, Germany, 2006.
- [39] N. Tas, J. Wissink, L. Sander, T. Lammerink, M. Elwenspoek, "Modeling, design and testing of the electrostatic shuffle motor", *Sensors and Actuators, A: Physical* 70 (1-2), 1998, pp. 171-178.
- [40] U. Simu, S. Johansson, "Analysis of quasistatic and dynamic motion mechanisms for piezoelectric miniature robots", *Sensors and Actuators A* (2006) In Press.
- [41] T. Lilliehorn, U. Simu, S. Johansson, "Multilayer telescopic piezoactuator fabricated by a prototyping process based on milling", *Sensors and Actuators A107* (2003) 159-168.