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50. Internationales Wissenschaftliches Kolloquium
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DEFLECTION MEASUREMENT OF PIEZOELECTRIC BENDING ACTUATORS WITH A COMBINATION OF AN INTEGRATED NON-CONTACT INDUCTIVE SENSOR AND HIGH-ACCURACY ELECTRONIC CIRCUIT

ABSTRACT

Low voltage piezoelectric multilayer beam bending actuators are suitable for a wide range of applications that require deflection in range of hundreds of microns. A variety of applications has been realized, for example in robotics, automotive and in health care. To use piezoelectric bending actuators the accurate control of the beam deflection is necessary. However the influence of hysteresis, non-linearities, creep, drift and external forces have to be compensated. In this paper we present a piezoelectric multilayer ceramic bender system with an integrated inductive sensor in combination with a high accuracy electronic circuit. The emphasis is laid on an optimized sensor output and a minimal influence of the sensor on the actuator performance. The size of the sensor with the electronic circuit allows the usage in applications where small dimensions of a sensing system are needed.

INTRODUCTION

The piezoelectric effect combines electrical and mechanical parameters. The conversion of mechanical deformation in electrical signals is named *direct piezoelectric effect*, The resulting deformation by applying an electric field is referred to as the *inverse piezoelectric effect*. These effects can be used for piezoceramic sensors and actuators offering a wide range of applications in all fields of electrical and mechanical design as well as acoustics, automation, communication, automotive, health care and consumer products.

The development of low drift piezoceramics reduced the effects of hysteresis and relaxation, but their piezoelectric coefficient does not allow the use for high efficient piezoceramic actuators. So the range of applications with low drift piezoceramics is limited because of small deflection and force.

For larger deflection and force a smart sensor-actuator-system is needed with a high efficient piezoelectric actuator and an integrated sensor in a closed regulation loop [1]. The usage of an integrated sensor allows detection and compensation of disturbing influences as inherent piezoelectric effects and external alternating forces and vibrations [2].

Existing capacitive measurement principles for the realization of a fed-back sensor-actuator system concerning piezoelectric multilayer beam bending actuators show small measuring effects.

So the requirements to the electronics of the capacitive sensor are enormous as far as resolution and electromagnetic shielding are concerned. Besides drift behavior of the electronics is difficult to prevent, thus in the regulation loop the actuator's influence of creep and drift can not be sufficiently compensated. Therefore we realized a non-contact inductive proximity sensor that is based on an especially developed ASIC. Fig. 1 shows an overview of the integrated inductive deflection sensor in combination with the bending actuator.

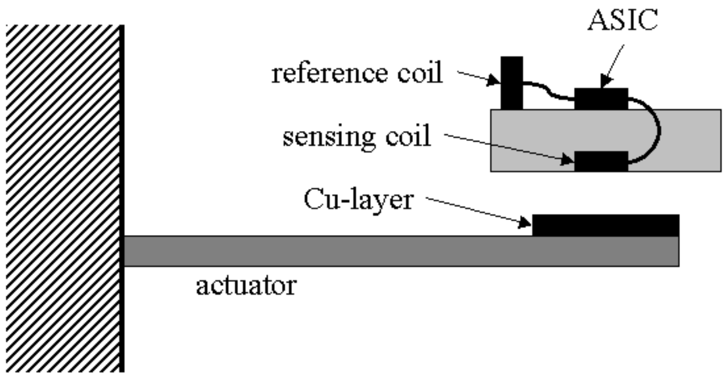

Figure 1: Overview of the integrated inductive deflection sensor in combination with the bending actuator

FUNCTIONALITY OF THE INDUCTIVE SENSOR

Functionality of the inductive proximity sensor

The inductive proximity sensor consists of a microelectronic circuit realized as an ASIC. Two 3D-mircocoils are connected to the ASIC. One of them acts as a sensing coil, the other one provides a reference. The quantity to be measured is the distance ξ to a conductive material. The output quantity is a frequency signal f_{out} on TTL level. In the following a material is considered that is electrically conductive and has a permeability $\mu_r = 1$.

The base of the sensor are two active resonant circuits. Each of them is built up of a wound coil and a microelectronic circuit that is part of the ASIC. Fig. 2 shows the schematics of the whole inductive proximity sensor. The microelectronic circuit of each resonant circuit is named *Oscillator 1* and *Oscillator 2* respectively. It consists of an integrated capacitor and an active cell that maintains the oscillation. The external coil completes the L-C resonant circuit. Principally, the oscillation frequency is given by equation (1).

$$f_0 = \frac{1}{2\pi\sqrt{L_{1,0}C}} \tag{1}$$

$L_{1,0}$ is the non-influenced inductance. The oscillation frequency f_2 of the reference circuit equals to

$$f_2 = \frac{1}{2\pi\sqrt{L_2C}} \,. \tag{2}$$

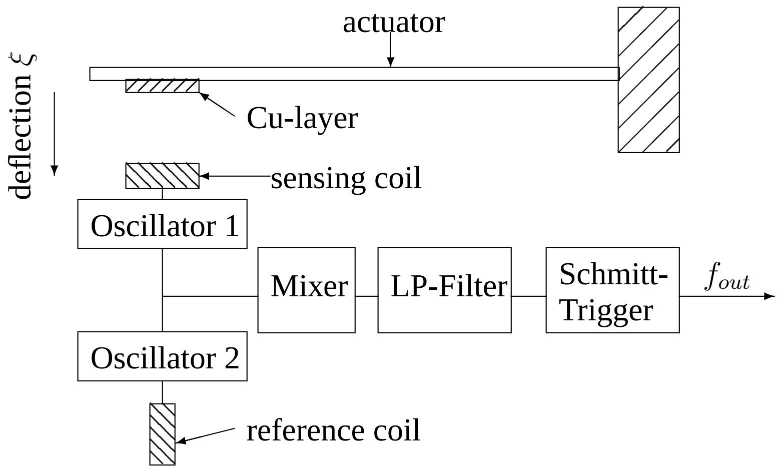

Figure 2: Schematics of the inductive proximity sensor and its surrounding conditions

In both circuits the capacitors are supposed to be equal.

Approaching of a conductive material the measuring coil, eddy currents are induced within the conductive material. They weaken the alternating magnetic field of the measuring coil that results in a decrease of the effective inductance $L_{1,\,0} - \triangle L_1$. According to (1) the oscillation frequency of the circuit increases (see eqns (4)and(4)). It should be mentioned that eqns (4)and(4)) are equivalent.

$$f_1 = \frac{1}{2\pi\sqrt{(L_{1,\,0} - \triangle L_1)C}} \tag{3}$$

$$f_1 = f_0\sqrt{\frac{L_{1,\,0}}{L_{1,\,0} - \triangle L_1}} \tag{4}$$

The basic dependency between the relative inductance change and the relative change of the oscillation frequency is described by equation (7). In the following the expression $f_{out}(\triangle L_1)$ is referred to the inductance change $\triangle L_1$ only.

$$\left|\frac{\triangle f(\triangle L_1)}{f(L_{1,\,0})}\right| = \left|\frac{\left|\frac{\partial f_1}{\partial L_1}\right|_{L_{1,\,0}} \triangle L_1}{f_1(L_{1,\,0})}\right| \tag{5}$$

$$\Leftrightarrow \left|\frac{\triangle f(\triangle L_1)}{f(L_{1,\,0})}\right| = \left|\frac{\frac{1}{2\pi\sqrt{C}}\left(-\frac{1}{2}\right)\frac{1}{L_{1,\,0}\sqrt{L_{1,\,0}}}\triangle L_1}{\frac{1}{2\pi\sqrt{C}}\frac{1}{\sqrt{L_{1,\,0}}}}\right| \tag{6}$$

$$\Leftrightarrow \left|\frac{\triangle f(\triangle L_1)}{f(L_{1,\,0})}\right| = \frac{1}{2}\left|\frac{\triangle L_1}{L_{1,\,0}}\right| \tag{7}$$

When decreasing the distance between the conductor and the coil from some centimeters to contact the relative inductance decrease can be in the range of 30% in case of micro flat coils, thus the maximal relative frequency increase can be in the range of 15%.

The difference of the oscillation frequencies of the two oscillators are evaluated by a following mixer (see Fig. 2). In order to reduce the noise of this signal it is low pass filtered and afterwards shaped by a Schmitt trigger [3]. The output frequency is given by equation (9).

$$f_{out} = |f_1 - f_2| \tag{8}$$

$$\Leftrightarrow f_{out} = |f(L_{1,0} - \triangle L_1) - f(L_2)| \tag{9}$$

In the following f_{out} is considered to be dependent on $L_1 = L_{1,0} - \triangle L_1$ and L_2. Analogically, the basic correlation for the relative output frequency change is given by equation (12).

$$\left|\frac{\triangle f_{out}(\triangle L_1)}{f_{out}(L_{1,0})}\right| = \left|\frac{\left|\frac{\partial f_{out}}{\partial L_1}\right|_{L_{1,0}} \triangle L_1}{f_{out}(L_{L_{1,0}})}\right| \tag{10}$$

$$\Leftrightarrow \left|\frac{\triangle f_{out}(\triangle L_1)}{f_{out}(L_{1,0})}\right| = \left|\frac{\frac{\triangle L_1}{2L_{1,0}\sqrt{L_{1,0}}}}{\frac{\sqrt{L_2}-\sqrt{L_{1,0}}}{\sqrt{L_{1,0}L_2}}}\right| \tag{11}$$

$$\Leftrightarrow \left|\frac{\triangle f_{out}(\triangle L_1)}{f_{out}(L_{1,0})}\right| = \left|\underbrace{\frac{\triangle L_1}{2L_{1,0}}}_{\to 15\%} \underbrace{\frac{\sqrt{L_2}}{\sqrt{L_{1,0}} - \sqrt{L_2}}}_{\gg 1}\right| \tag{12}$$

On the one hand the magnitude of the relative frequency change depends on the influence of the conducting target towards the inductance of the sensing coil. On the other hand the inductance difference between the two oscillators determines the magnitude of frequency change which can be extremely influenced by the choice of the the inductance L_2 and $L_{1,0}$. The combination of the two coils' nominal inductances determines the scale factor of the sensor. If their inductive reactances are close to each other a small change of the effective inductance L_1 can affect a huge modification of the output frequency.

Performance of the output signal

In our measurement setup f_{out} equals 360 kHz if the coils are not influenced by a conducting material. As shown in Fig. 2 a copper foil of 40 μm thickness with the dimensions 4 mm x 5 mm was applied close to the beam bender's tip. Minimizing the distance ξ between the coil and the copper layer up to some microns results in a maximum output frequency f_{out} = 660 kHz.

For an easier understanding in the following the dependency of the output frequency against the deflection ξ is supposed to be linear, though in reality this correlation is more complex. Furthermore the output frequency ist scaled down by the factor $\frac{1}{10}$ to get a better impression of the basic operation mode of the sensor electronics. So for the further description f_{out} ranges from 36 kHz up to 66 kHz.

The beam bender is supposed to be driven by a sine signal of 2 kHz. An offset is added to the sine signal, so the piezoelectric ceramic layers of the actuator are not exposed to tensile stresses, thus in Fig. 2 the bender only deflects upwards. If there is no deflection (ξ = 0 μm) the minimal frequency output is f_{out} = 36 kHz. This is the origin for further discussions. At maximum deflection of 300 μm the copper layer almost contacts the coil and f_{out} equals 66 kHz. The bender's tip deflection is shown in Fig. 3. Accordingly, f_{out} shows the behavior that is sketched in

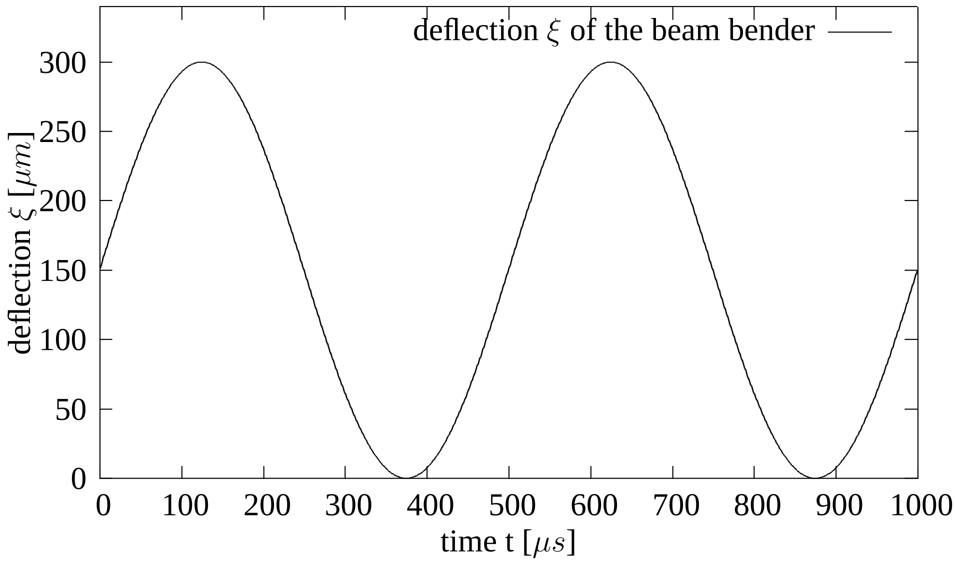

Figure 3: Calculated deflection ξ of the beam bender's tip according to a driving voltage V_{dr} of 2 kHz

Fig. 4. The phase signal at the output of the sensor electronics is considered in the following step. The frequency f_{out} is a function of time consisting of the carrier frequency f_c (here 51 kHz) and the modulation frequency f_{mod} (here 2 kHz). The frequency deviation f_{dev} due to the modulation equals 15 kHz. So the output frequency can be described by the following equation

$$f_{out}(t) = f_{dev}\sin(2\pi f_{mod}t) + f_c \tag{13}$$

In order to determine the phase signal $\varphi_{out}(t)$ the angular frequency $\omega_{out}(t) = 2\pi f_{out}(t)$ has to be integrated with respect to time. At the moment t=0 the phase φ_{out} is assumed to be equal to zero. So we get

$$\begin{aligned} \varphi_{out}(t) &= \int_0^t \omega_{out}(t')dt' && (14)\\ &= 2\pi \int_0^t \left(f_{dev}\sin(2\pi f_{mod}t') + f_c\right)dt' && (15)\\ &= 2\pi \left[-\cos(2\pi f_{mod}t')\frac{f_{dev}}{2\pi f_{mod}} + f_c t'\right]_0^t && (16)\\ &= \frac{f_{dev}}{2f_{mod}}(1-\cos(2\pi f_{mod}t)) + 2\pi f_c t && (17) \end{aligned}$$

Equation (17) describes the behavior of the phase signal $\varphi_{out}(t)$ at the output of the sensor electronics. This is also shown in Fig. 5.

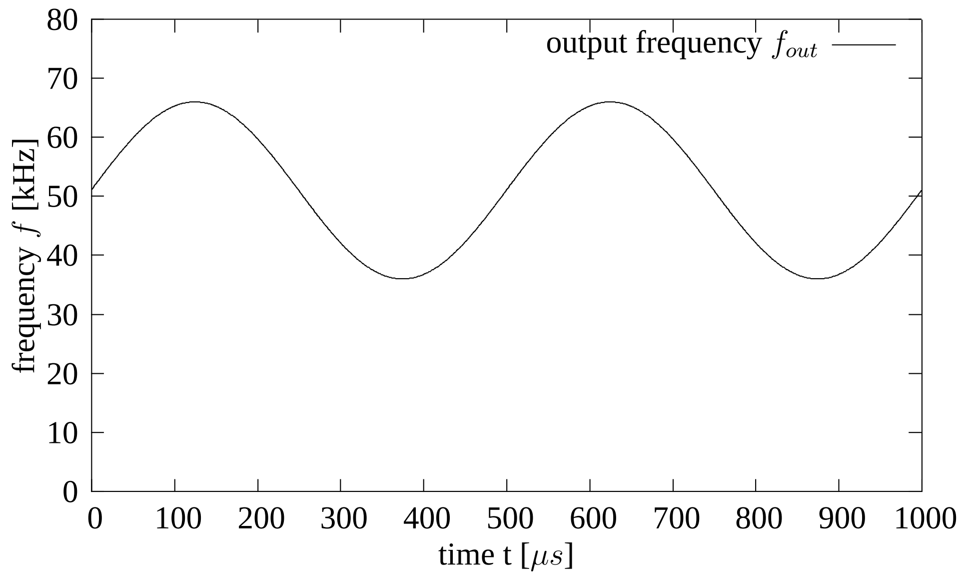

Figure 4: Calculated output frequency f_{out} of the ASIC influenced by the 2 kHz oscillation of the bender's tip

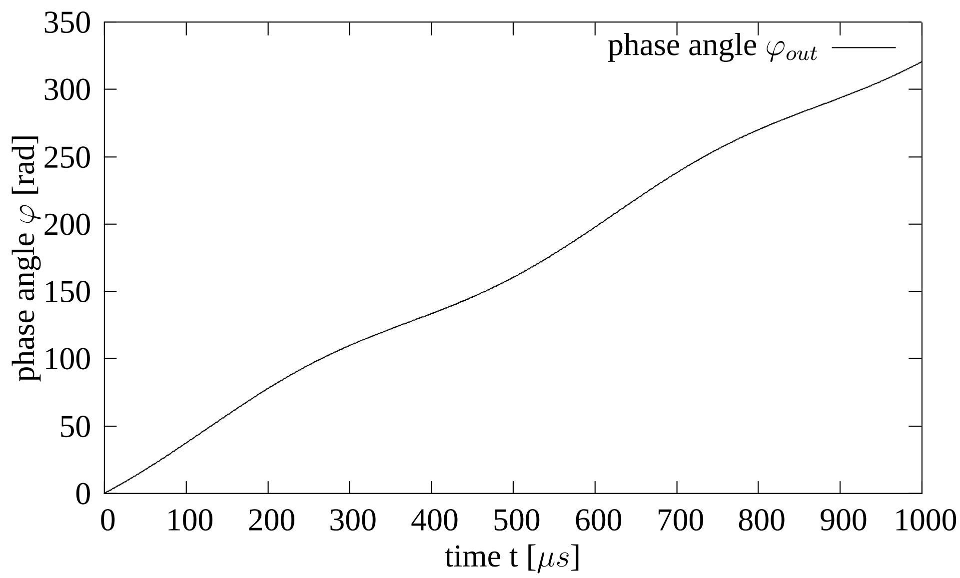

Figure 5: Calculated phase angle $\varphi_{out}(t)$ as a function of time assuming φ_{out}(t = 0) = 0

In order to reduce the noise of the real output signal it is low-pass filtered and afterwards shaped by a Schmitt trigger. The shaped signal equals to

$$V_{out} = 2,5\ \mathrm{V} \cdot \mathrm{sign}(\sin(\varphi_{out})) + 2,5\ \mathrm{V}\ . \tag{18}$$

The modulation frequency f_{mod} within the output voltage V_{out} is a quantity for the deflection ξ. This behavior is also shown in Fig. 6. This frequency modulated signal on TTL-level has to be read analyzed.

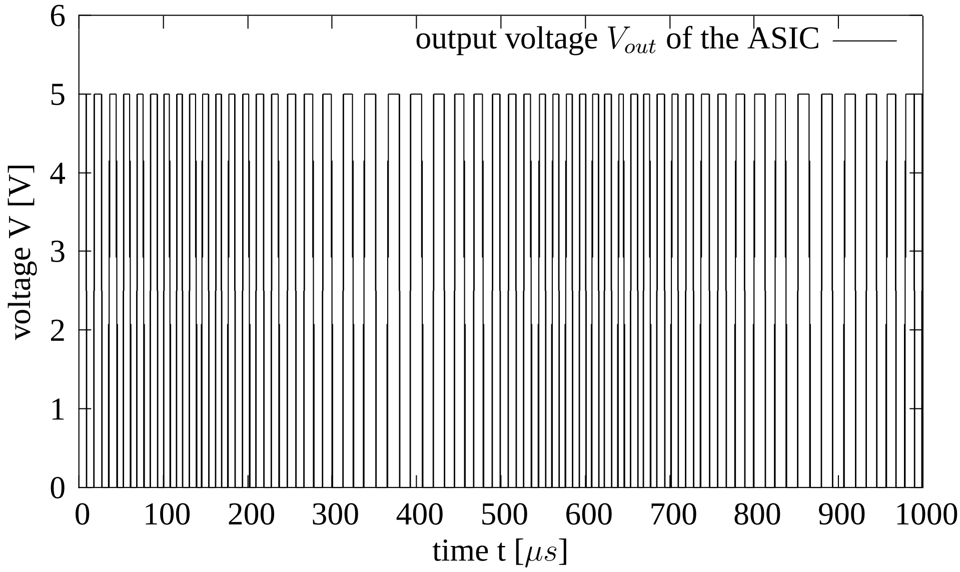

Figure 6: Calculated TTL output signal with respect to the frequency scale factor of $\frac{1}{10}$

MEASUREMENTS

Measurement setup

The measurement setup of the actuator-sensor system is shown in Fig. 7. Applying a voltage to the actuator by the piezo driver results in a bending movement of the beam. So the distance between the copper layer and the sensing coil decreases. The sensor electronics converts the tip deflection ξ into the output frequency f_{out}. On the one hand this frequency can directly be interpreted by the counter of the I/O-board as it is shown in Fig. 7. On the other hand a f/V-converter and an analog filter can generate a voltage signal that can be acquired by the I/O-board. In order to quantify the real deflection ξ, the measurements have always been verified by a high precision laser deflection measurement system.

Measurement results

Fig. 8 shows the achieved measurement results of the tip deflection of a piezoelectric bending actuator after calibration.

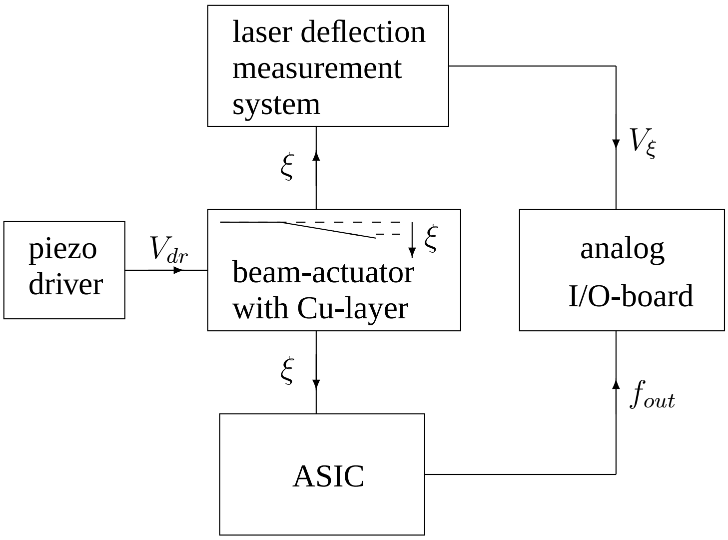

Figure 7: Measurement setup for the inductive deflection measurement of a piezoelectric bending actuator

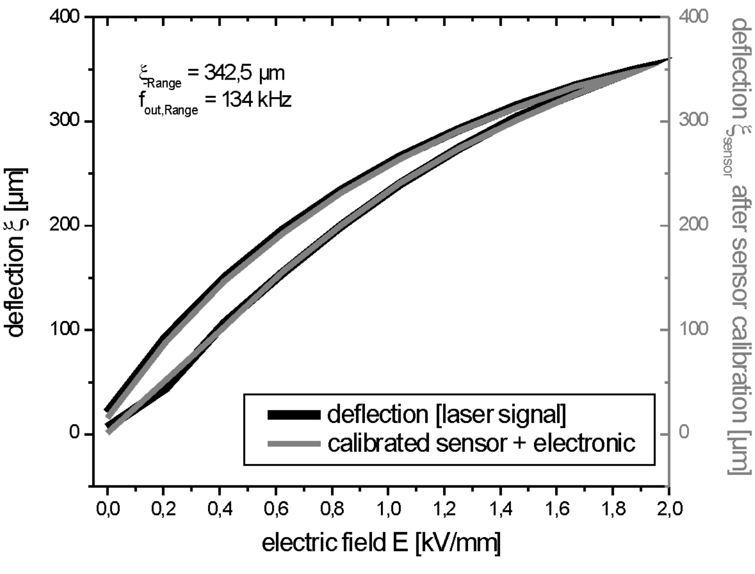

Figure 8: Deflection measured and the calibrated output signal of the sensor vs. electric field E applied

CONLUSION

Our tests have shown the suitability of an integrated non-contact inductive sensor to measure the deflection of a piezoelectric bending beam actuator. With this combination of a piezoelectric micro actuator and an integrated inductive sensor a broad spectrum of applications can be generated, e.g. the control of the air flow in a micro valve (see Fig. 9).

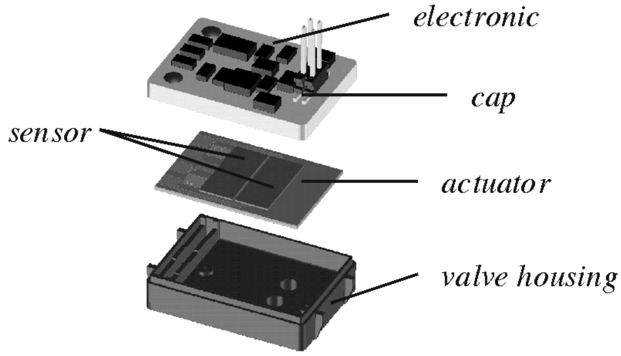

Figure 9: Micro valve with an piezoelectric micro actuator with an integrated sensor to control the air flow

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