Observer Techniques Applied to the Control of Piezoelectric Microactuators

Micky Rakotondrabe, *Member, IEEE,* Cédric Clévy, *Member, IEEE,*
Ioan Alexandru Ivan, *Member, IEEE,* and Nicolas Chaillet, *Member, IEEE,*

***Abstract*— We present here the use of sensors, observers and self-sensing techniques to control piezoelectric actuators, particularly piezocantielevers.**

First, the feedback control with full measurements (all variables are measured) is presented. Because of the lack of convenient sensors for the microworld, nonfull measurements combined with observer techniques is proposed. Finally, the self-sensing principle, where the actuator is at the same time sensor, is applied and used for the feedback.

I. Introduction

The need of high performances micro/nano robots and systems increases rapidly. These new technologies can be used for applications such as micromanipulation (of artificial components and biological objects), microassembly (of MEMS, MOEMS, NEMS), material and surface force characterization, biological analysis, etc. At the micro/nano scales, sensing is a key issue to control systems and to understand physical phenomena. Numerous sensors with suitable resolution and range are necessarily required.

This paper give a survey on the sensing and measurement possibilities for microsystems. We particularly focus on piezoelectric based actuator with cantilevered structure. The concern variables are the displacement and the force.

Section II introduces the main but very influent specificities of the microscale. Current technical and physical limitations are explained and consequences on micro/nano robots and systems are given. Several state of the art solutions are investigated including these specificities. Section III introduces the full measurement, i.e. where sensors display direct and suitable measured information, and its use to the control of piezoelectric actuators. When direct measurement is not available, observers are required. Several applications of observer techniques for piezoelectric actuators are introduced in Section IV. Finally, we present the self-sensing technique where the piezoelectric actuator is also the sensing element. In this case, no external sensor is necessary. However, an electronic circuit followed by a convenient observer scheme is used to provide the estimate force and/or the displacement. This technique is presented in Section V.

FEMTO-st Institute,
UMR CNRS-6174 / UFC / ENSMM / UTBM
Automatic Control and Micro-Mechatronic Systems department (AS2M department)
25000 Besançon - France
{mrakoton, cclevy, alex.ivan, nicolas.chaillet}@femto-st.fr

II. Microscales specificities

Micro/nano robots and systems require specific studies and developments. Indeed, the down scaling greatly influences the required specifications for and the behavior of robots and systems. For example, assembly of human sized systems is generally done by hand for technico-economical optimization reasons whereas assembly of microsized components requires robotized systems assistance. Thus, the development of automated microassembly systems constitutes a key issue in the development of new micro-assembled products which is not the case at the macro scale [1]. Microscale systems or systems acting at the microscale therefore require the integration of actuators and sensors.

At the microscale, systems have to achieve positioning accuracy and resolution in the submicrometer range and forces in the micro-nano Newton range. Moreover, some applications require high dynamic performances and then high bandwidth sensors, for instance the automation of piezoelectric based micromanipulation robots. Unfortunately, sensors that guarantee these performances are bulky and expensive (interferometers, scanning electron microscopes, cameras, laser sensors). Furthermore, most of these sensors generally enable only one or 2D measurements. On the other hand, sensors that are compact and convenient for packaging (strain gage, piezoceramic sensor, etc.) are very fragile and have very limited performances and robustness. In addition, scaling down decrease signal to noise ratio. Specific studies to understand the sources of noises and to find solutions to take them into account become of great importance. Moreover, surface force becomes predominant at the microscale. For example, they can reach 200 μN for 50x50 μN^2 planar contacts [2]. These forces are for the most influent, capillary pull-off and van der Waals forces. The lack of models, knowledge and experimentations at the microscale is a source of great difficulties for applications like micromanipulation and microassembly [3].

All of these microscale specificities therefore require developments of new sensors and sensing principles taking into account suitable range, resolution, free space, and dynamic [4].

III. Presentation of the piezoelectric actuators used in this paper

In the sequel, we are interested by the measurement/observation and control of displacement and force in piezoelectric cantilevers (piezocantilevers) especially dedicated to micromanipulation and microassembly tasks, where the range of displacement is up to some hundred of μm and the range of force up to several tens of mN. Cantilevered piezoelectric actuators are used in different applications: AFM-piezotubes, microgrippers, tweezers, stepper (stick-slip and inch-worm) microrobots, etc. Even if we use a unimorph piezocantilever with rectangular section in this paper, the techniques can be applied to other cantilevers.

A unimorph piezocantilever is made up of one piezoelectric layer, often Lead Zirconate Titanate (PZT) ceramic, and one passive layer. Commonly used passive layers is Nickel. When applying a voltage U to the piezolayer, it expands/contracts resulting a global deflection δ of the cantilever (Fig. 1). Furthermore, a force F applied at its tip also results a deflection.

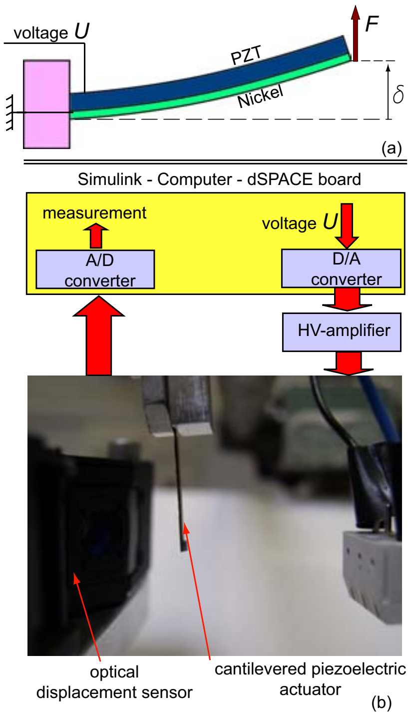

Fig. 1. A unimorph piezoelectric cantilever.

IV. Full measurement and control applications

We mean by full measurement the fact that all suitable signals used for the feedback control are directly measured by sensors. The main part of this section is to give a survey of sensors that can be used to control piezoelectric based actuators, especially piezocantilevers.

A. Existing sensors

1) Pinpoint measurement: they concern measurement that measure one point of the actuator. To measure the displacement δ, optical displacement sensors are very common (Fig. 1-b). It can offer up to $10nm$ of resolution and $\pm 150\mu m$ of range [5]. If the tasks need a higher resolution and range, an interferometer measurement system can be the solution. For applications which require the force control, femto-tools force sensors are adapted [6].

2) Vision-based measurement: despite the high resolution of the optical and the femto-tools sensors, they are limited to measure one point of the actuator. So, they could not be used to search the location of the object when there is not yet contact between the latter and the actuator, or when the contact point has changed. To surpass this limitation, vision based measurement have been used [7]. This technique can measure both the location of the object and the displacement/deformation of the actuator.

The main disadvantages of the optical, the vision based measurement and the femto-tools sensors are their bulky sizes and their relatively high costs. As a result, they are not adapted for packaged high performances microsystems. This is why embarked sensors have been developed. They are cited below.

3) Strain gauges: they are glued on the surface of the piezoelectric cantilever and the displacement or force at its tip is easily deduced. The offered resolution and the accuracy depend on the number of the used gauges, of the quality of the Wheatstone bridge and of the electronic amplifier. Thanks to the low costs and the small sizes of strain gauges, they have been used in numerous applications in the field of micromanipulation and microassembly [8][9][10]. Finally, *Arai et al.* developed multi-axis strain gauges dedicated to complex micromanipulation [11]. The main disadvantages of strain gauges are their fragility and their high sensitivity to noises.

4) Piezoelectric sensors: it consists in putting two couples of electrodes on the surfaces of the piezocantilever. While one couple is used to supply the voltage input for the actuation, the second one is used to measure the output charge for the displacement/force sensing. These sensors provide a high bandwidth [12]. However, they are not adapted to static measurement because of the drift (creep) characteristics [13]. Piezoelectric sensors can be based on classical piezoelectric materials such as PZT [14][15] or PVDF (PolyVinylidine DiFluoride) [16][17].

5) Capacitive sensors: an alternative way of embarked sensors is based on the capacitive principle. Similarly to the piezoelectric sensor, it can be designed and developed with the same bulk than the actuator. In fact, the sensing element and the actuation element are made of the same material making them very adapted to microfabrication techniques [18].

6) Piezomagnetic sensors: these sensors are based on transducers whose the magnetization changes when a mechanical stress is applied [12]. An example of piezomagnetic sensor is given in [19].

B. Commonly used control techniques

Because the measurement (displacement or force) constitutes the variable to be controlled, output feedback with controllers in cascade are often designed (Fig. 2-a). They ranges from PID structure with a trial and error tuning to advanced H_∞ control laws, with or without accounting the nonlinearities in the piezoelectric actuators [20][21][22]. The results (Fig. 2-b) are convenient to the specifications required in micromanipulation and microassembly, such as micrometric accuracy and some tens of millisecond of settling time.

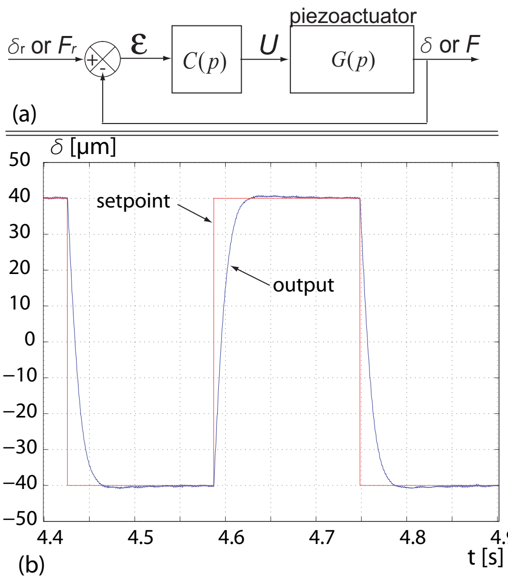

Fig. 2. (a) bloc scheme of the output feedback control using controllers in cascade. (b) a series of step response of the closed-loop.

C. Limitation of the used sensors

On the one hand, high accuracy sensors are expensive and bulky (optical, interferometer, etc.). On the other hand, small sensors are fragile and very sensitive to noises (strain gauges, etc.). Furthermore, some applications necessitate the measurement of both displacement and force during the tasks, as example during a pick-and-place task, and therefore necessitate many sensors.

In order to gain space and to go to the packageability of the microsystems, two approaches were proposed: 1) the use of small sensors (strain gauges) and the rejection of the noises using the Kalman filtering, 2) the use of reduced number of sensors and the application of observers to complete the measurement. The next section is focused on these points.

V. Observers and non-full measurement

In this section, we consider that one or more variables used for the feedback is not directly measured. The use of observer techniques is therefore advised.

Reconsider the piezocantilever presented in Fig. 1. The model linking the input voltage U, the force F applied at the tip and the output deflection δ, in the linear case, is:

$$\delta = d_p.U.D(s) + s_p.F.D(s) \quad (1)$$

where d_p and s_p are the piezoelectric and the elastic coefficients respectively, and $D(s)$ (with $D(0) = 1$) is the dynamic part.

When the applied electrical field -through the voltage U- is high, the nonlinearities behavior of the piezoelectric materials becomes nonnegligible. These nonlinearities are the hysteresis and the creep and need to be taken into account when applying an observer. The nonlinear model of the actuator is therefore [21]:

$$\delta = H(U).D(s) + C_r(s).U + s_p.F.D(s) \quad (2)$$

where $H(\cdot)$ is an operator that describes the (static) hysteresis and $C_r(s)$ is a linear approximation of the creep.

A. Strain gauges sensors, Kalman filtering and state feedback control

In [23], strain gauges were used to measure the deflection δ of the piezocantilever with a view to reduce the sizes of the whole microsystems (actuators and sensors). To reduce the noises of the measured signals, the authors apply a Kalman filtering computed with the linear model (equ 1). In addition to the noises rejection, the technique allows the estimation of the states of the system and therefore allows the use of state feedback control techniques (Fig. 3).

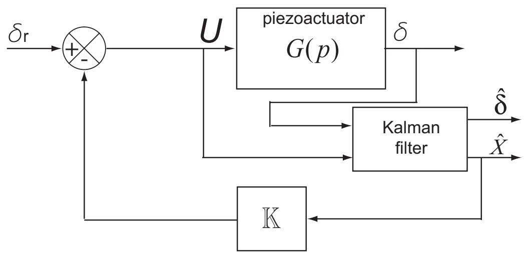

Fig. 3. Measurement of δ with strain gauges and use of a Kalman filter.

B. Force estimation using the Luenberger observer

In [24], two piezocantilevers forming a microgripper were used. While one piezocantilever is used to accurately position the manipulated object, the second one is used only to estimate the manipulation force (Fig. 4-a). To estimate the input force, the latter has been considered as a state of the system. Because a derivative is required in the state equation, the author considers the condition $\frac{dF}{dt} = 0$. As a result, the state vector is composed of the deflection δ, its derivative $\frac{d\delta}{dt}$ and the force F. Based on the model in (equ 1), a Luenberger observer has been applied (Fig. 4-b).

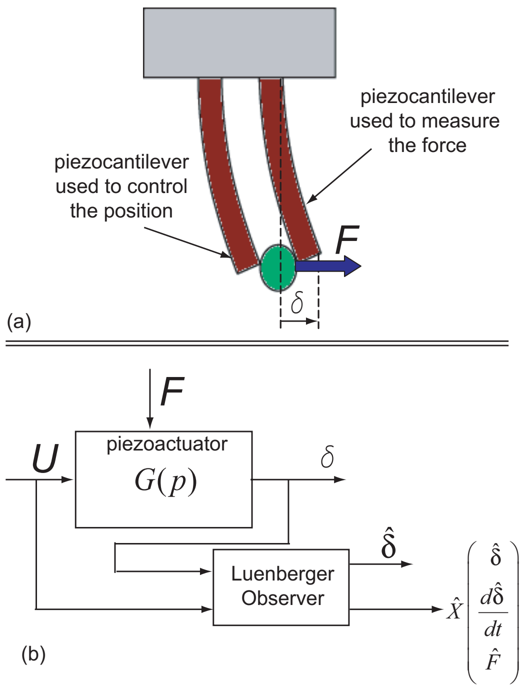

Fig. 4. (a) use of one piezocantilever of the microgripper to estimate the manipulation force. (b) estimation of the force using the Luenberger observer.

C. *Force estimation and Unknown Input Observer technique (UIO)*

When the force is considered as a state to be estimated, it requires that the dynamics model of the force is known. In the previous case, the derivative of F has been considered to be null and the estimation was only valuable for static case. It has also been demonstrated that the dynamics of the force in piezocantilevers always depend on the characteristics of the manipulated object [25]. Therefore, considering the force as a state is not convenient if the estimate will be used in a control purpose. This is why the Unkown Input Observer techinque (UIO) has been proposed recently [26]. The Inverse-Dynamics-Based UIO technique [27] was especially applied. In this, we consider the force as an unknown input. A classical observer is first employed to estimate the state vector (composed of the deflection and its derivative). Afterwards, a second observer is applied to estimate the force (Fig. 5).

D. *Force estimation in the nonlinear case, open loop Observer*

In [28], another approach was proposed to estimate the force. It consists in using the nonlinear model in (equ 2)) and directly deducing the force:

$$\hat{F} = \frac{1}{s_p.D(s)}\left(\delta - H\left(U\right).D(s) - C_r\left(s\right).U\right) \qquad (3)$$

where the hysteresis $H(\cdot)$ was modeled by the Bouc-Wen approach.

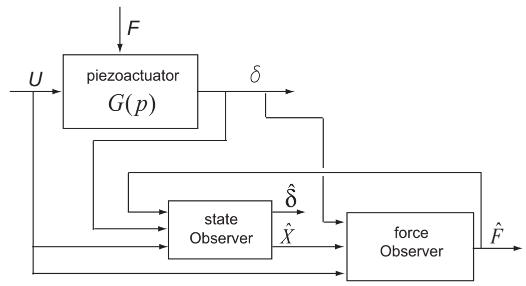

Fig. 5. Inverse-Dynamics-Based UIO technique to estimate the unknown input force.

This method requires the bistability of $D(s)$ as its inverse is used in the (open-loop) observer. If the system is linear, the method can also be applied. Indeed, the term d_pU of (equ 1)) is a linear approximation of the hysteresis term $H(\cdot)$ in (equ 2)), the creep $C_r(s)$ being set to zero.

As presented in Fig. 6, the observer has an open-loop structure, and therefore is sensitive to model uncertainty.

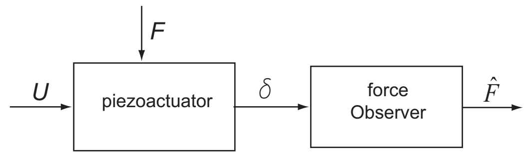

Fig. 6. Nonlinear open-loop observer.

E. *Application to control*

The Luenberger observer for the estimation of δ and $\frac{d\delta}{dt}$ was successfully used in a state feedback control law of the displacement [24]. References [25][29][30] used successfully the nonlinear open-loop observer to estimate the force and to apply H_∞ based controllers.

VI. Self-sensing based control

As shown above, accurate sensors are often bulky and expensive while integrable ones are fragile and not robust. There exist an alternate, simple and cost-effective up-grade solution for most types of existing piezoelectric actuators: the self-sensing technique.

A. *Principle of the self-sensing*

It consists in using the actuator as also the sensor. The principle is as follows. When a voltage U and/or an external force F are applied to the piezocantilever, it bends. Charges Q also appear at its surface. Using a charge amplifier (electronic circuit) and a convenient observer, it is possible to estimate both the dipslacement and the force [41]. This "intrinsic technique" can therefore be used in a closed-loop system without needing external sensors.

Often charge measurement is rejected on false idea that PZT is a very bad isolating material. In fact, not the leaking resistivity, which is high enough for preserving charges (hundreds of seconds) but ferroelectric material non-linearities (hysteresis, creep) or the temperature influence put the challenge on the charge-based self-sensing.

B. Historical of the self-sensing

The first use of "self-sensing" term dates back to 1992 when *Dosch et al.* [31] successfully damped the vibration of a piezoelectric beam without the aid of external sensors. Voltage drop provided from a capacitive bridge was processed in an analog circuit, amplified and returned back to the piezoelectric element. Soon, several independent applications began to emerge for beam vibration control or micropositioning of piezo stacks. Several years later *Takigami et al.* [32] applied the method to force self-sensing and control a large size bimorph actuator, using a half-bridge circuit, a voltage follower and PC-based data acquisition system. They experimentally shown that the stiffness of the manipulated object does not affect the measurement. However, the electronic circuit limited the applied voltage range and the nonlinearities (hysteresis and creep) of the piezoelectric element were not compensated.

A self-sensing based on integrator electronic circuit was introduced in [33] focusing on a compounding control of displacement combining a PID feedback control with a feedforward control of hysteretic behavior. Self-sensing force control for piezo stack was introduced in [34][35]. In the latter paper, the hysteresis nonlinearity was taken into account by using the generalized Maxwell-slip hysteresis operator [36]. As a result, the static displacement error was reported to 2 to 4% while static force error is nearly 5%. In [37], a modified bridge electronic circuit with adaptable gain was intended for vibration control under structural deformation. In [38], self-sensing technique was used to ameliorate the positioning and vibration in hard-disk drives. Finally, in [39], the use of self-sensing microdispensing system shows better positioning performance than the use of external sensors.

Other sensorless methods close to self-sensing concept consist in shaping several electrodes on the actuator and dedicating them separately for actuation or sensing [14] (see also the *Section-IV.4. Piezoelectric sensor*). The drawback is that a fraction of the actuation capability is lost. However, the nonlinear effects are avoided and signals are well separated. More recently a SPM piezotube scanner with a new electrode pattern allowed self-measurement of nanometer resolution with improved transfer function in the observer [40].

C. Static displacement/force self-sensing

Most of the above papers focused on short-term (less than 1s) displacement and/or force self-sensing control or vibration damping. Until our recent works ([41] for the displacement self-sensing, [42] for the displacement and force self-sensing), there was a lack of publications related to long term self-sensing of piezoelectric cantilevers intended for microsystems manipulation. In quasistatic (low frequency) regime, the electric charge over the electrodes of the uni- or bimorph piezocantilever is intrinsically proportional to the free displacement. The main ferroelectric nonlinearities (hysteresis, creep) are automatically included. Thus, there is no need to compensate the hysteresis and creep of the actuators. The electronic circuit and the observer presented in [41](Fig. 7) relies on the current integration and compensation of the second-degree nonlinearities such as PZT leaking resistance, bias currents and dielectric absorption. The temperature influences was also discussed in the paper, and the attained accuracy was 0.5% over a period of 600 seconds. In [42] we reported the simultaneous force-displacement self-sensing of the piezo cantilever entering in contact with an object. For that purpose, we modeled the nonlinear behaviour of the free actuator (including hysteresis and creep operators) and fused the result with the electronic signal, deriving the estimate force and displacement.

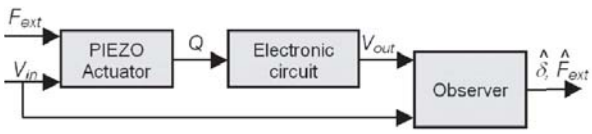

Fig. 7. Generic principle of a self-sensing system [41].

D. Dynamic displacement self-sensing

The method proposed in [41] was upgraded in [43] in order to complete the static displacent self-sensing by the dynamic part (Fig. 8). The estimate signal can be therefore used control applications.

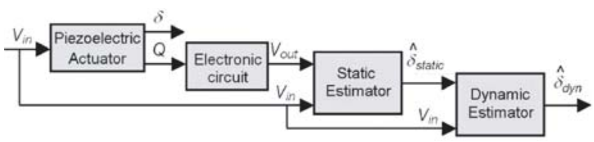

Fig. 8. Extension of the static self-sensing in [41] to dynamic self-sensing [43].

E. Discussion

To sum up, the first advantage of self-sensing is the cost, external sensors not being needed anymore. System will be more flexible in terms of space occupation, allowing better miniaturization and dexterity in terms of DoF. Also, actuators dynamics will no longer be affected by mechanically attached sensors (e.g. strain gages or micromangnets). Number of connecting cables will be reduced. Disadvantages consist in adding a supplementary electronic circuit (but of reduced complexity). Electronic circuit is based on a capacitive bridge (or divider) or a current integrator. Specific applications with dedicated electrodes for sensing (such as in *Section-IV.4. Piezoelectric sensor*) may measure directly strain-induced voltage. Attention has to be paid for preserving the charge as long as possible. Non-linearities such as hysteresis and creep due to ferroelectric domain relaxation put the most challenge on self-sensing technique, limiting its accuracy, especially in force sensing. Identifying these nonlinear effects requires an extra procedure. Finally, temperature influence, noise or other uncertainties may prevent the system to attain required accuracy or resolution.

VII. Conclusion

This paper presented the different methods that have been used to measure, observe and sense the signals (especially force and displacement) in piezoelectric actuators and particularly piezocantilevers.

We first presented the existing sensors that can be used. They offer a full-measurement based control applications. Afterwards, we shown that observers can be used to complete the measurement when some signals are not directly measured. Finally, the self-sensing techniques - that can be applied when no sensor is available- were presented and end the paper.

References

[1] D. O. Popa, R. Murthy, and A. N. Das 'M3 - Deterministic, Multiscale, Multirobot Platform for Microsystems Packaging: Design and Quasi-Static Precision Evaluation' IEEE Transaction on Automation Science and Engineering, 2009 , 6 , 345-61

[2] K. Rabenorosoa, C. Clévy, P. Lutz, M. Gauthier and P. Rougeot 'Measurement setup of pull-off force for planar contact at the microscale' Micro-nano letters, vol(4), Issue(3), pp:148-154, septembre 2009

[3] M. Gauthier, S. Regnier, P. Rougeot and N. Chaillet ŚForces analysis for micromanipulations in dry and liquid mediaŠ, J. Micromechatronics, 2006, 3, pp. 389Ű413

[4] F. Beyeler, S. Muntwyler, and B.J. Nelson, 'Design and Calibration of a Microfabricated 6-Axis Force-Torque Sensor for Microrobotic Applications', IEEE ICRA (International Conference on Robotics and Automation), 2009.

[5] http://www.keyence.fr/

[6] http://www.femtotools.com/

[7] Y. H. Anis, J. K. Mills and W. L. Cleghorn, 'Visual measurement of mems microassembly forces using template matching', IEEE ICRA (International Conference on Robotics and Automation), 2006.

[8] M. Goldfarb and N. Celanovic, 'A flexure-based gripper for small-scale manipulation', Robotica, 17, 1999.

[9] A. Menciassi, A. Eisinberg, M. C. Carrozza and P. Dario, 'Force sensing microinstrument for measuring tissue properties and pulse in microsurgery', IEEE/ASME Transactions on Mechatronics, 2003.

[10] P. Berkelman, L. L. Whitcomb, R. H. Taylor and P. Jensen, 'A miniature microsurgical instrument tip force sensor for enhanced force feedback during robot-assisted manipulation', IEEE Transactions on Robotics and Automation, 2003.

[11] F. Arai, A. Kawaji, T. Sugiyama, Y. Onomura, M. Ogawa, T. Fukuda, H. Iwata and K. Itoigawa, '3d micromanipulation system under microscope', IEEE International Symposium on Micromechatronics and Human Science, 1998.

[12] M. Motamed and J. Yan, 'A review of biological, biomimetic and miniature force sensing for microflight', IEEE IROS, 2005.

[13] C. K. M. Fung, I. Elhajj, W. J. Li and N. Xi, 'A 2-d pvdf force sensing system for micromanipulation and microassembly', IEEE ICRA, 2002.

[14] D. Campolo, R. Sahai and R. S. Fearing, 'Development of piezoelectric bending actuators with embedded piezoelectric sensors for micromechanical flapping mechanisms', IEEE ICRA, 2003.

[15] K. Motoo, F. Arai, Y. Yamada, T. Fukuda, T. Matsuno and H. Matsura, 'Novel force sensor using vibrating piezoelectric element', IEEE ICRA, 2005.

[16] D-H. Kim, B. Kim, S-M. Kim and H. Kang, 'Development of a piezoelectric polymer-based sensorized microgripper for microassembly and micromanipulation', IEEE IROS, 2003.

[17] A. Shen, N. Xi, C. A. Poumeroy, U. C. Wejinya and W. J. Li, 'An active micro-force sensing system with piezoelectric servomechanism', IEEE IROS, 2005.

[18] Y. Sun, B. J. Nelson, D. Potasek and E. Enikov, 'A bulk microfabricated multi-axis capacitive cellular force sensor using transverse comb drive', Journal of Micromechanics and Microengineering, 2002.

[19] M. Lohndorf, T. Zuenas-Lockwood, A. Ludwig, M. Ruhrig, D. Burgler, P. Grunberg and E. Quandt, 'A novel strain sensors based on magnetostrictive gmr/tmr structures', IEEE International Magnetics Conference, 2002.

[20] M. Rakotondrabe, C. Clévy and P. Lutz, 'H-inf deflection control of a unimorph piezoelectric cantilever under thermal disturbance', IEEE/RSJ - IROS, (International Conference on Intelligent Robots and Systems), pp:1190-1197, San Diego CA USA, Oct-Nov 2007.

[21] M. Rakotondrabe, Y. Haddab and P. Lutz, 'Quadrilateral modelling and robust control of a nonlinear piezoelectric cantilever', IEEE - Transactions on Control Systems Technology (T-CST), Vol.17, Issue 3, pp:528-539, May 2009.

[22] M. Rakotondrabe, J. Agnus, K. Rabenorosoa and N. Chaillet, 'Characterization, modeling and robust control of a nonlinear 2-dof piezocantilever for micromanipulation/microassembly', IEEE/RSJ - IROS, (International Conference on Intelligent Robots and Systems), pp:767-774, St Louis MO USA, October

[23] Y. Haddab, Q. Chen and P. Lutz, 'Improvement of strain gauges micro-forces measurement using Kalman optimal filtering.', IFAC Mechatronics, 19(4), 2009.

[24] Y. Haddab. 'Conception et réalisation dŠun système de micromanipulation contrôlé en effort et en position pour la manipulation dŠobjets de taille micrométrique'. PhD dissertation (in French), University of Franche-Comté, Laboratoire dŠautomatique de Besancon, 2000.

[25] Micky Rakotondrabe, Yassine Haddab and Philippe Lutz, 'Modelling and H-inf force control of a nonlinear piezoelectric cantilever', IEEE/RSJ - IROS, (International Conference on Intelligent Robots and Systems), pp:3131-3136, San Diego CA USA, Oct-Nov 2007.

[26] M. Rakotondrabe and P. Lutz, 'Force estimation in a piezoelectric cantilever using the inverse-dynamics-based UIO technique', IEEE - ICRA, (International Conference on Robotics and Automation), pp:2205-2210, Kobe Japan, May 2009.

[27] C-S. Liu and H. Peng, 'Inverse-dynamics based state and disturbance observers for linear time-invariant systems', ASME Journal of Dynamics Systems, Measurement and Control, vol.124, pp.375-381, September 2002.

[28] M. Rakotondrabe, I. A. Ivan, S. Khadraoui, C. Clevy, P. Lutz, and N.Chaillet, 'Dynamic Displacement Self-Sensing and Robust Control of Cantilevered Piezoelectric Actuators Dedicated to Microassembly Tasks', Submitted in IEEE/ASME AIM (Advanced Intelligent Mechatronics), 2010.

[29] M. Rakotondrabe, C. Clévy and P. Lutz, 'Modelling and robust position/force control of a piezoelectric microgripper', IEEE - CASE, (International Conference on Automation Science and Engineering), pp:39-44, Scottsdale AZ USA, Sept 2007.

[30] M. Rakotondrabe and Y. Le Gorrec, 'Force control in piezoelectric microactuators using self scheduled H_∞ technique', ASME Dynamic Systems and Control Conference and IFAC Symposium on Mechatronic Systems, MIT 2010.

[31] J. J. Dosch et al., "A Self-Sensing Piezoelectric Actuator for Collocated Control", J. of Intell. Mater. Syst. and Struct., vol 3, pp. 166-185, 1992.

[32] T. Takigami et al., "Application of self-sensing actuator to control of a soft-handling gripper", Proc. to IEEE ICCA, pp. 902-906, Italy, 1998.

[33] Y. Cui et al. " Self-sensing compounding control of piezoceramic micro-motion worktable based on integrator", Proc. to 6th World Cong. On Intell. Con. and Autom., China, 2006.

[34] A. Badel et al. "Self sensing force control of a piezoelectric actuator", IEEE Trans. on UFFC, vol. 55, no. 12 Pp. 2571-2581, 2008.

[35] A. Badel et al., "Self-sensing high speed controller for piezoelectric actuator", J. of Intell. Mater. Syst. and Struct., vol 19, no. 3, pp. 395-405, 2008.
[36] M. Goldfarb and N. Celanovic, " Modeling piezoelectric stack actuators for control of micromanipulation", IEEE Control Systems Magazine, vol.3, no.3, pp.69-79, 1997.
[37] W.W. Law, W-H. Liao and J. Huang, "Vibration control of structures with self-sensing piezoelectric actuators incorporating adaptive mechanisms", Smart Mater. Struct 12, pp. 720-730, 2003.
[38] C. K. Pang et al., " Self-sensing actuation for nanopositioning and active-mode damping in dual-stage HDDs", IEEE/ASME Trans. on Mechatronics, vol. 11, no. 3, pp. 328-338, 2006.
[39] A. S. Putra et al., " With Adaptive Control in Applications With Switching Trajectory" , IEEE/ASME Trans. on Mechatronics, vol. 13, no. 1, pp. 104-110, 2008.
[40] S. O. R. Moheimani and Y. K. Yong, "Simultaneous sensing and actuation with a piezoelectric tube scanner", Review of Scientific Instruments 79, 073702, 2008
[41] I. A. Ivan, M.Rakotondrabe, P. Lutz and N. Chaillet, "Quasi-static displacement self-sensing method for cantilevered piezoelectric actuators", Review of Scientific Instruments (RSI), Vol.80(6), 065102, June 2009.
[42] I. A. Ivan, M.Rakotondrabe, P. Lutz and N. Chaillet, "Current integration force and displacement self-sensing method for cantilevered piezoelectric actuators", Review of Scientific Instruments (RSI), Vol.80(12), 2126103, December 2009.
[43] M. Rakotondrabe, I. A. Ivan, S. Khadraoui, C. Clévy, P. Lutz and N. Chaillet, "Dynamic displacement self-sensing and robust control of cantilevered piezoelectric actuators dedicated to microassembly tasks", IEEE/ASME - AIM, (International Conference on Intelligent Materials) 2010.