Micro/Nanopositioning Systems with Piezoelectric Actuators and Their Role on Sustainability and Ecosystem

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Abstract

Micro/nanopositioners based on piezoelectric actuators and their role to preserve the biodiversity of the ecosystem and achieve a sustainable manufacturing sector are presented in this chapter. These positioners are precise at micro/nanometre resolution and have improved and assisted reproduction and somatic cell nuclear transfer, playing an increasingly important role in preserving endangered species from extinction. Studies suggest these technologies are potentially key factors in our ability to decelerate degradation of our nature. Further, piezo-actuated micro/nanopositioners are the foundation of add-on accuracy increasing systems, which can return outdated machine tools to service, with minor changes and at a performance level higher than new machines. This avoids (and can further prevent) waste of energy and materials, as the outdated machines or their major parts would otherwise be deposed of. In addition, piezo-actuated micropositioners play an essential role in vibration-assisted machining, which reduces energy consumption, increases product quality and extends machine life times.

Introduction

Nano/micropositioning aims at control of position at the nano/micrometre scale for applications such as fine machining [1], manipulation of biological cells [2] , scanning probe microscopy [3] and robotic surgery [4]. Different types of actuators such as magnetostrictive actuators[5] and worm gears [6] have been used in nano/micropositioning. However, piezoelectric actuators are the least bulky, most precise and now the most common actuators for nano/micropositioning [7]. The technology also has a high potential to contribute to environmental sustainability.

Piezo-actuated micro/nanopositioning systems may include (i) a piezoelectric actuator, which deforms in relation to its input electrical voltage, (ii) a sensor to obtain the position of (a point or a surface on) the piezoelectric actuator, and (iii) a control system which provides the required excitation voltage to realise the desired position. Of these three components, the actuator and the control system are essential and sensors may be excluded [8, 9] . Choice of the designer in respect of any of these components affects the performance, expense and performance of the nano/micro positioner.

Role of Piezo-actuated Micro/nanopositioning Systems in Biodiversity Protection and Sustainable Manufacturing

Biodiversity Protection

Biodiversity and maintaining an intact biodiverse ecosystem have a direct link to health and sustainable development. According to recent research [10], more than one million species are currently at risk of extinction, and losing any takes our ecosystem one step closer to an irreversible degradation. Recent developments in biotechnology, particularly in cell manipulation, has aided species preservation [11] with assisted reproductive techniques (ARTs) such as intracytoplasmic sperm injection (ICSI), in vitro fertilisation (IVF), cryopreservation of gametes, artificial insemination, and embryo transfer are being used extensively to increase the population of endangered animal species [12].

Piezo-actuated micro/nanopositioning systems are employed in cell manipulation and play a crucial role on increasing the performance and success rate of ART methods [13]. For instance, in ICSI, a single spermatozoon of the species is injected to the cytoplasm of a mature oocyte as shown in Fig.1. Use of a piezo-actuated nanopositioner (attached to the needle) for injection improves the performance of the system [14]. With the use of a piezo-actuated nanopositioner, wider pipes (with outer diameters up to $30\ \mu m$) can be successfully driven into the plasma without a membrane break; this is almost impossible in the conventional ICSI, where needle size is restricted to only few micrometres [14]. Piezo-actuated ICSI systems provide a precise and fast motion for the tip of the needle with speeds of nearly $40\ \mu m/s$; this facilitates control of the procedure as the sperm tail oolemma is disrupted in a well-controlled manner rather than manually. Positive effects of using piezo-actuated nanopositioners on the outcome of ICSI procedures have been reported [14, 15]. As an instance, a recent study [16] clearly indicates the significant increase of fertilisation rates with use of piezo-actuated micro/nanopositioning systems in ICSI when compared to conventional ICIS; and that piezo-ICSI reduces the rate of oocyte degeneration and abnormal fertilisation.

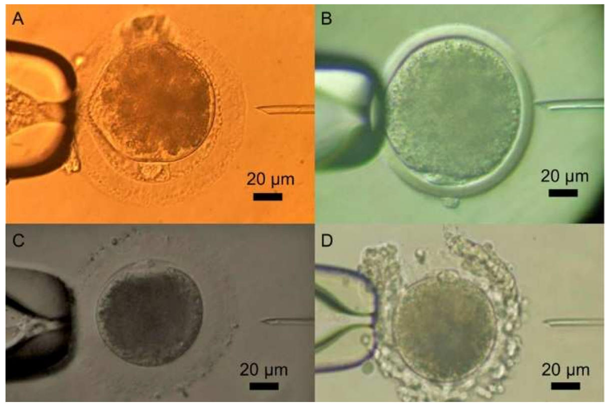

Figure 1: .ICIS set up and oocyte of different species (A) Equine oocyte, (B) ovine oocyte, (C) domestic cat oocyte and (D) leopard oocyte. PB, polar body [15]

Somatic cell nuclear transfer (SCNT) is another emerging and promising technique for maintaining biodiversity and to tackle the issue of the extinction and endangerment of many species [17]. SCNT could also be used not only for saving the endangered species [18], but as an effective tool for reproduction of genetically valuable animals, generation of transgenic species and manufacturing modern medicines [18]. SCNT cloning also has a great potential to help in fighting new diseases like Covid-19 [19]. As depicted in Fig. 2, nuclear DNA is removed from an oocyte and replaced by a somatic cell nucleus. There are two main methods to place a somatic cell nucleus into an oocyte: (i) conventional electrofusion of the somatic cell to the cytoplasm of the oocyte and (ii) one-step micromanipulation (OSM) as depicted in Fig .2. Research has revealed that the latter provides better efficiency and leads to higher in vitro blastocyst development rate [20]. In OSM,

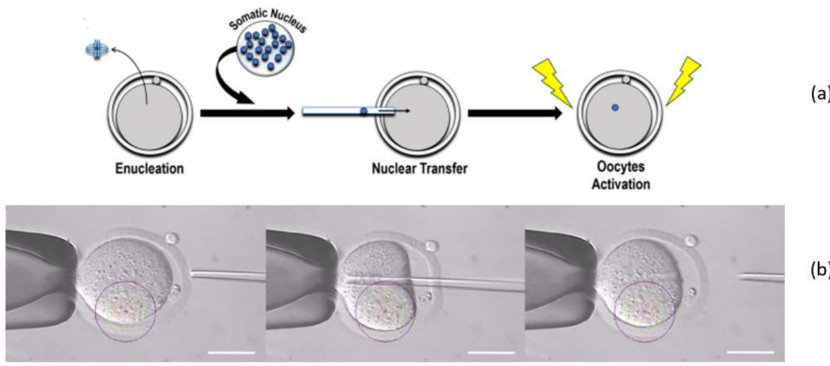

Figure 2: (a) different steps in somatic cell nuclear transfer (SCNT) [18], (b) donor cell injection process [22]

the needle tip is usually driven by a piezo-actuated micromanipulator. Figure 3 shows a typical experimental setup for SCNT. An piezo-actuated micropositioner is mounted on the injection micropipettes for both enucleation of the somatic cell and nuclear transfer to oocytes [21].

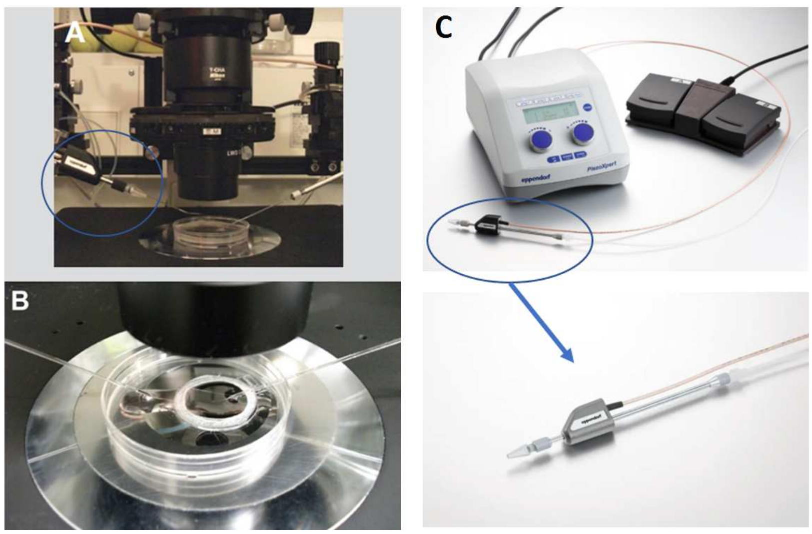

Figure 3: a) Micromanipulation chamber and setup for somatic cell nuclear transfer (SCNT) to oocytes including micropipettes (b) holding pipette (right) and enucleation or nuclear transfer micropipette (left) coupled to (c) piezoelectric micromanipulating system Eppendorf PiezoXpert [21]

Sustainable Manufacturing

Sustainable manufacturing and production systems also benefit from the technical attributes of piezo-actuated micro/nanopositioning systems. Machine tools significantly influence sustainability, social, economic and environmental issues [23]. A third of the worldwide energy consumption and CO_2 emissions is in the production industry, where machine tools are major role players [24]. The use of outdated machine tools, common in developing nations, leads to a considerable waste of energy and raw materials [24]. The constant replacement or retrofitting of machine tools consumes material and energy resources, a threat to sustainable growth. According to the International Energy Agency (IEA), there exists significant potential for energy and raw material saving through the upgrade and reuse of these outdated machine tools without extensive modification or replacing their core components [25]. Upgrading existing machine tools with minor changes, as an alternative method to retrofitting and refurbishment, can considerably improve sustainability aspects of manufacturing processes [26].

One of the major issues with outdated machine tools is insufficient positioning accuracy. In outdated machine tools mis-positioning errors yield low quality machined products, the main reason for their replacement, retrofitting and major overhaul [25]. A sustainable solution to this problem is to use an add-on system to compensate for these positioning errors and such add-ons are often based on piezo-actuated micropositioners. As an example, a piezo-actuated add-on accuracy increasing system (AAIS), shown in Fig.4(b) was introduced [24], as a sustainable solution. This is a modular station with high accuracy in error compensation that can be easily mounted the work table of a machine to upgrade it and improve its functionality, as shown in Fig. 4(a) [23]. Fig. 4(c) shows that an outdated machine with an AAIS may perform even better than a new machine tool, in terms of positioning accuracy. The add-on not only increases the precision of positioning but also acts as an active control system to diminish chatter and avoid stick-slip problems [24], increasing the life span of the machine and further sustainability. An AAIS consists of a series of sensors measuring kinetic (forces and torques) and kinematic (displacement, velocity and acceleration) errors of the machine during its operation. A control unit separate from the main control unit of the machine analyses these errors and commands a high stiffness two-dimensional piezo-actuated micropositioning system mounted on the AAIS table, as depicted in

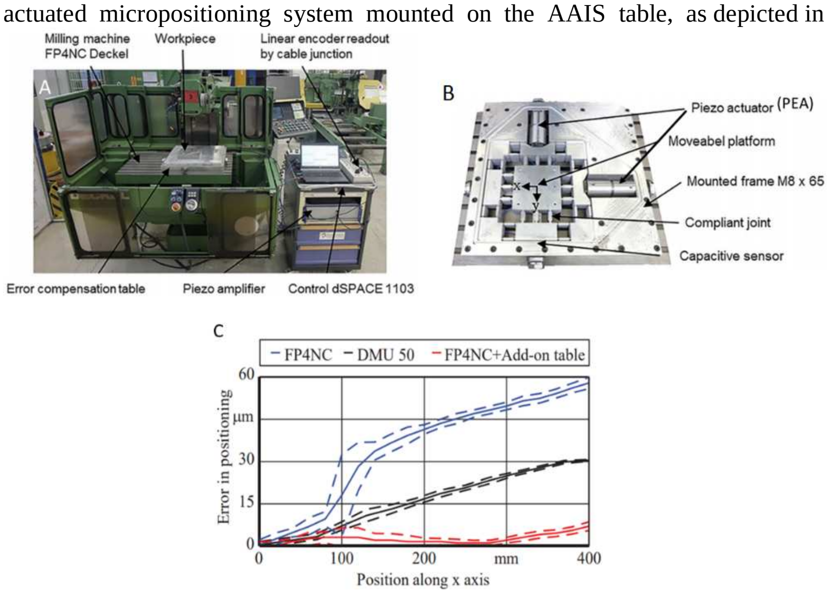

Figure 4: a) AAIS set up mounted on a milling machine FP4NC, FRIEDRICH DECKEL AG, München, Germany [23](b) Error compensation table with piezoelectric actuators in two directions (x,y) [24](c)measured positioning error in the x-axis of the set up for FP4NC (old) , upgraded FP4NC (FP4NC+AAIS) and a new DMU 50 milling machine[24]

Fig.4(a). Add-ons, including piezo-actuated micropositioners can be widely used to upgrade all different types of machine tools. This considerably reduces raw materials and energy consumption as well as CO_2 emission, but avoids replacing or retrofitting outdating machines without loss of product quality.

In addition to improved positioning accuracy and reduction of chatter, piezo-actuated micro/nanopositioning systems can enhance manufacturing sustainability with a realisation of vibration-assisted machining (VAM), as depicted in Fig.5. In VAM, a precise low amplitude, high frequency vibration in the cutting direction is applied on the cutting tool [27] to create a reciprocating motion at the tip. For a specific combination of amplitude and frequency and feed velocity, the tip of the tool periodically gets detached from the work piece, reducing machining forces, friction and heat, improving the surface finish and increasing the accuracy [27]. VAM also increases tool life span and leads to almost zero burr [28]. For the frequencies (> 5 kHz) and vibration amplitudes (<50 μm) required by VAM, piezo-actuated micropositioners attached to the tool tip or the worktable are the best candidates to generate the required vibrations.

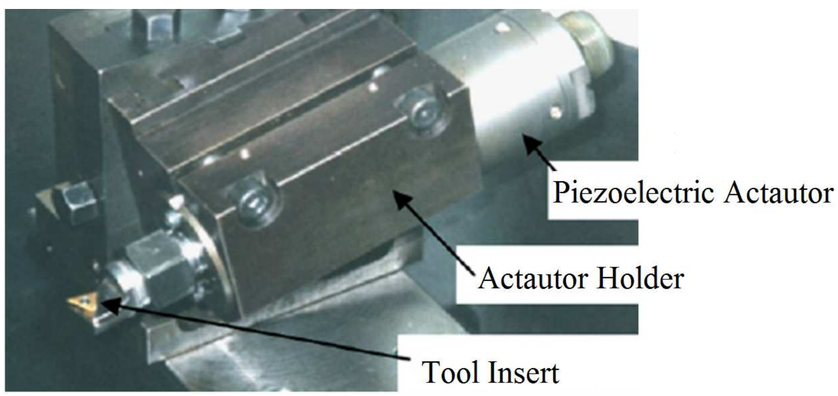

Figure 5: Schematic of a piezo-actuated micropositioner/vibrator for VAM [29]

Different Types of Piezoelectric Actuators in Micro/nanopositioners

Piezoelectricity, the interaction of mechanical and electrical quantities in piezoelectric materials, was discovered in the 1880s for quartz by the French physicists, the Curie brothers [30]. Currently, quartz [31] and other crystals [32] are still used to produce piezoelectric materials. These materials are also produced with piezoceramics (e.g. barium titanate, $BaTio_3$), ferroelectric polycrystalline ceramics and most commonly with lead zirconate titanate (PZT) [30].

The piezoelectricity phenomenon is rooted in the asymmetrical distribution of electrons within ions of particular materials [33]. As a result of this, in piezoelectric materials application of either mechanical force or an electrical voltage results in the generation of a voltage or mechanical deformation and force. Generation of deformation or force due to an applied voltage is known as inverse piezoelectricity[34]. Piezoelectric materials intentionally produced to use inverse piezoelectricity are called piezoelectric actuators[35].

Piezoelectric actuators are the foremost actuators in nano/micropositioning due to their nanometre displacement resolution, large bandwidth, fast response and high stiffness [36]. There are three types of piezoelectric actuators commercially available as follows.

Piezoelectric Stacks

Stacks are composed of layers of a piezoelectric material [37] and are commonly coated with polymers [38]. Stack piezoelectric actuators are stiff and easy to use for nano/micropositioning purposes [7]. Stacks with various shapes have been used including rectangular prism [39], cylinder [38] or ring [40]as shown in Fig. 6. As a rule of thumb, maximum deflection of rectangular prism stacks is generally slightly greater than 0.1% of their length [38]. The relationship between applied voltage on a stack piezo actuator and its deflection has been repeatedly reported to be highly nonlinear [39].

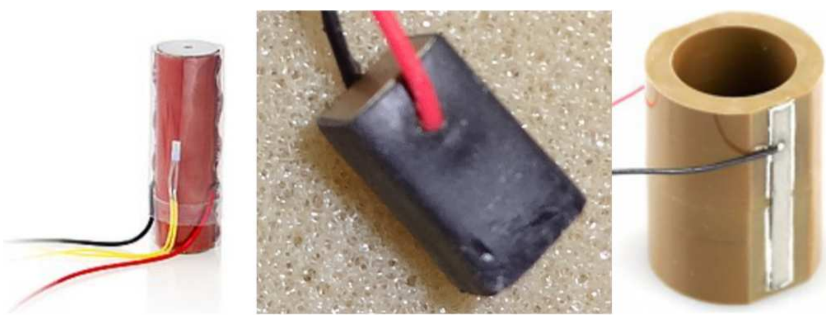

Figure 6: Stack piezoelectric actuators with the shape of a cylinder [41] (left) ,a rectangular prism (middle) and a ring [38] (right)

Piezoelectric Tubes

Piezoelectric tubes are made of a metal cylinder covered by piezoelectric material internally and externally. The inner layer is continuous and grounded, as depicted in Fig. 7. The outer layer is divided into a number of (e.g. 4 [42] or 12 [43]) segments or electrodes. These actuators should be differentiated from piezo stack with a long ring or tube shape [38]. Piezoelectric tubes can deflect in three directions. Nevertheless, they are quite fragile; thus, these actuators need more care and occasionally more complicated stands for operation [33]. Piezoelectric tubes are widely used for probe scanning microscopy [44], particularly in atomic force microscopy [45]. The first natural or resonance frequency of the tubes employed in atomic force microscopy is in the range of 200-1500 Hz [46], though relatively short piezo tubes may exhibit first natural frequencies up to hundreds of kilohertz [47]. A large piezoelectric tube (e.g. 100 *mm* long and with an outer diameter of 15 *mm*) is likely to produce displacements of up to 100 micrometres. For some tube piezo actuators, the relationship between applied voltage and produced deflection has been reported to be slightly nonlinear [42] or nearly linear [44].

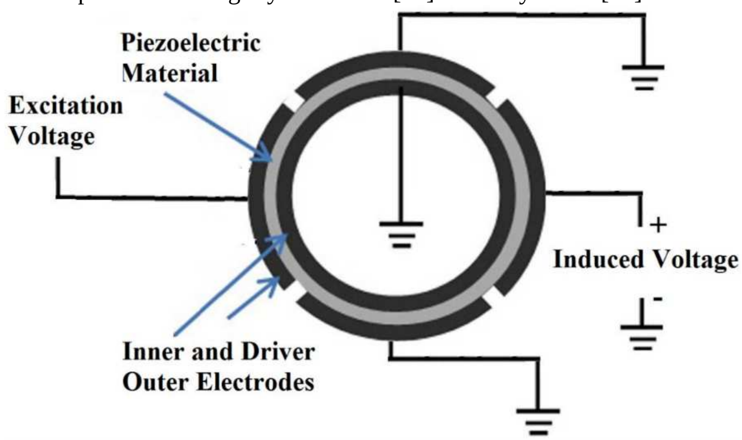

Figure 7: Cross section and electrical connections of a piezoelectric tube actuator [48]

Piezoelectric Benders

Piezoelectric benders may be composed of one, two or multiple piezoelectric plate(s) and possibly thin layers of shim or metal [49]. Benders with rectangular [49] or circular [50] sections, depicted in Fig.8, are commercially available. Piezoelectric benders with one (two) piezoelectric plate(s) are known as unimorph (bimorph) benders [35] and have been widely used in micro and nanopositioning [35]. High deflection and low natural frequency, in comparison with tubes and stacks, are the two main characteristics of benders, i.e., a typical piezoelectric bender can have a maximum deflection of 2mm [38] and a first natural frequency in the range of tens to hundreds of hertz [38].

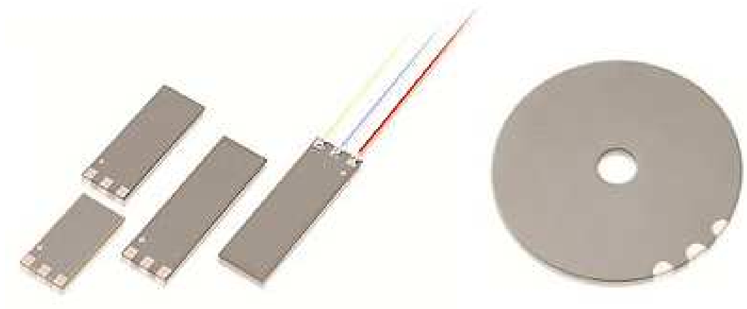

Figure 8: Piezoelectric benders [50]

Different Types of Sensors used in Micro/nanopositioners

Two categories of sensors may be used in micro/nanopositioning: (1) sensors with mechanical contact and (2) contact-less sensors.

Sensors with Mechanical Contact

Strain gauges and precise Linear Differential Variable Transformers (LVDTs) are suitable candidates for the measurement with mechanical contact, which are detailed in the following.

Strain Gauges

These inexpensive sensors originally measure strain; however, since the dimensions of the actuators are much larger than their deflections, they are widely used as displacement or position sensors [51]. The resolution of a precision strain gauge is approximately 1 micron (10^{-6}) [52]; thus for a piezoelectric stack with a length of 5 cm (5×10^{-2} m), a strain gauge can measure displacements as small as 50 nm ($10^{-6}\times5\times10^{-2}$ m). Although, the strain gauge can be bonded to the actuator surface, any misalignment between the longitudinal axis of the strain gauge with the strain direction of the piezoelectric stack needs to be compensated. Furthermore, the strain gauges need a resistive bridge box, similar to the one in Fig.9, and special amplifiers to provide measurable voltage [53]. In addition, dummy gauges are needed to compensate the effect of both environmental magnetic fields and thermal stress.

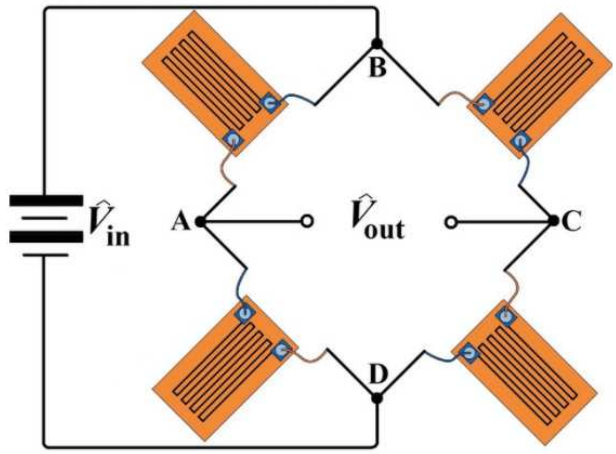

Figure 9: A bridge strain gauge circuit [54]

Linear Differential Variable Transformer (LVDT)

LVDT is one of the most reliable and robust displacement sensors. An LVDT, shown in Fig.10(a), consists of a primary coil, two secondary coils and a ferromagnetic core connected to a non-ferromagnetic stem [55]. To measure displacement, the tip of LVDT's plunger, Fig.10(b) is attached to the target. The variation of the rectified output voltage of the secondary coil is proportional to the displacement of the target. LVDTs have a relatively low price (approximately US$ 1000) and long life span; however, they are not recommended for motions with frequencies higher than 1 kHz [56].

Figure 10: (a) Internal structure of LVDT (b) real photo of LVDT [57]

Contactless Sensors

Contact-less measurement can be conducted with optical sensors (e.g., laser triangular sensor, laser interferometer, and fibre optic) and capacitive sensors, introduced in the following subsections:

Laser Triangulation Sensor

Laser triangulation sensors have a range of accuracies and resolutions. Resolutions of 1 nm at the sampling frequency of 392 kHz are achievable with a triangular laser sensor[58]. Compared to a laser interferometer, its reference distance (the required gap between the sensor tip and the target) is smaller; however, its lower cost (US$10,000) and easy initial setup makes it attractive for many nano/micropositioning applications.

Laser Doppler Vibrometer

Laser Doppler Vibrometers (LDVs) are the most precise commercially available position sensors providing sub-nanometre resolution. However, they are expensive, costing at least US$ 20,000 and measure velocity rather than position/displacement. To find position, the velocity must be integrated which potentially leads to drift. Nevertheless, laser vibrometers offer a large reference distance and have been successfully employed in nanopositioning [59].

Fibre Optic Displacement Sensor

Fibre optic displacement/position sensors can reach resolutions as small as 8 nm [60] and have been reported to be successfully used in nanopositioning [8]. These sensors need to be calibrated before each use [61], itself a precise operation. A fibre optic sensor with its essential accessories, including a proper amplifier, costs around US$ 1,000.

Capacitive Sensor

Capacitive sensors measure the capacitance between two metal surfaces and map the change of capacitance into displacement. They may provide resolutions as small as 1nm [62]. This type of sensor is widely used in nanopositioning due to their high accuracy and reasonable price (e.g. below $2,500) [42].

Control System of Micro/nanopositioners

Figure 11 depicts a nano/micropositioning system in term of control. The control system may receive three types of inputs:

1) Desired position, normally as a function of time [42].
2) Position signal from a position/displacement sensor, non-existent in some control systems.
3) Voltage signals collected from the piezoelectric actuator, some or all of these signals are non-existent in some control systems. These signals are (i) the voltage across the piezoelectric actuator, known as the piezoelectric voltage [63] (V_P in Fig.12), (ii) the voltage across an electrical element in series with the piezoelectric actuator, known as the sensing voltage [64] (V_S in Fig.12), and (iii) the voltage induced on a non-excited segment or electrode of a piezoelectric tube actuator (unavailable in other types of piezo actuates), known as the induced voltage.

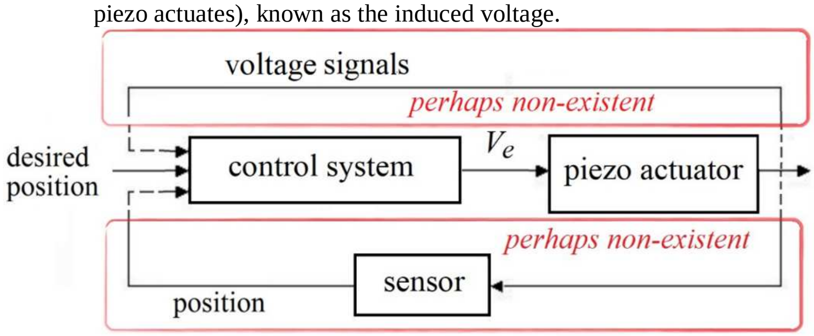

Figure 11: A schematic of a piezo-actuated nano/micropositioning system

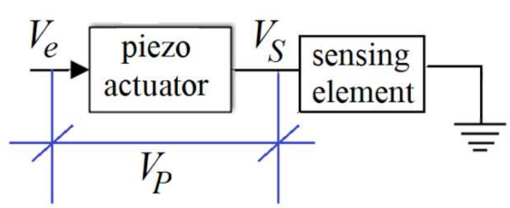

Figure 12: Excitation, piezoelectric and sensing voltages (V_e, V_P and V_S) in a circuit. The sensing element, if exists, is a part of the control system.

There are two major approaches to controlling piezo-actuated nano/micropositioners: (i) voltage-based and (ii) charge-based [7]. In voltage-based approach (e.g. [42]), the position is directly controlled through tuning of V_e . However, in charge-based approach (e.g. [65]), the desired position is mapped into the desired charge, and then charge is controlled through tuning of V_e.

Voltage-based Approach

Voltage-based control systems are widely used for piezo-actuated nano/micropositioners with different control architectures and controller types. Figures 13 and 14 depict two feedback voltage-based control systems with use of a sensor (conventional feedback) and a position estimator, respectively. Nonlinear controllers [66] have been used in feedback control systems, similar to the ones of Figs. 13 and 14, due to their inherited nonlinearity. Figure 15 depicts a feedforward control system, which uses neither a measured position nor a voltage signal.

Development of position estimators for piezoelectric actuators is still a challenge; the reason is the complexity of the relationship between the voltage signals and position. Some researchers have tried to explain and model this relationship through three separate phenomena: vibration, hysteresis and creep [45]. Several physics-based [67] and data-driven [39, 42, 68-70] methods have been tried to estimate the position using one [70, 71] or a number of voltage signals [8, 65], and this area of research is still active [72]. Amongst the voltage signals, V_P has been tried most to estimate position, e.g. in [69-71, 73].

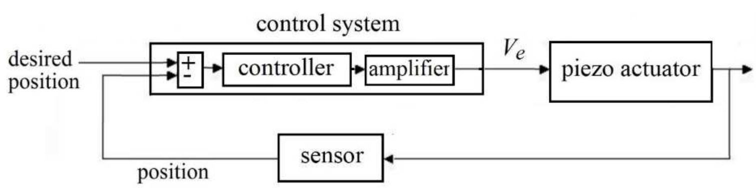

Figure 13: A schematic of a conventional feedback voltage-based control system for a piezo-actuated nano/micropositioner

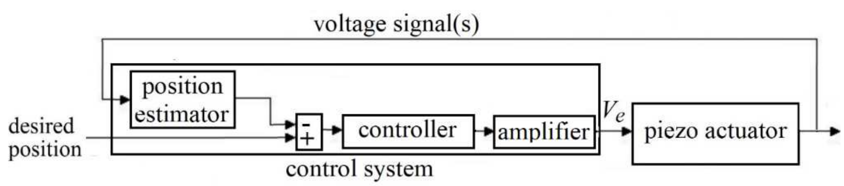

Figure 14: A schematic of a feedback voltage-based control system for a piezo-actuated nano/micropositioner with use of estimated position

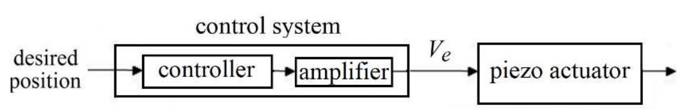

Figure 15: A schematic of a feedforward voltage-based control system for a piezo-actuated nano/micropositioner

Charge-based Approach

Figure 16 depicts the schematics of a charge-based control system for piezo-actuated nano/micropositioners. In this approach, position control is divided into two problems:

(i) Mapping position to piezoelectric electric charge,

(ii) Charge control through tuning V_e .

Regarding point (i), advantageously, charge and position are proportionally related in wide operating areas for many piezoelectric actuators. This simplifies charge-position mapping to identification/use of a simple gain.

Regarding point (ii), estimation and control of charge can be performed within an electrical circuit with no need to involve complexities of voltage-position relationship, e.g. hysteresis and … [74] . In this approach, V_S is used to estimate charge, rather than to deform the actuator. As a result, V_S is also called voltage drop.

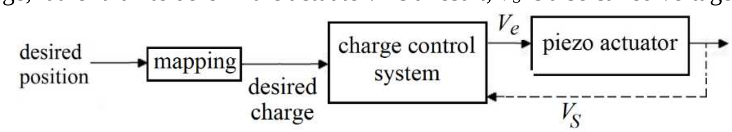

Figure 16: A schematic of a charge-base piezo-actuated nano/micropositioning system

Summary of Control Systems' Section

Both voltage-based and charge-based control approaches have been successfully used for piezo-actuated nano/micropositioners. Each has its own advantages, as briefly listed in Table 1.

Table 1: Relative Advantages of Different Approaches to Piezo-actuated nano/micropositioners

Relative Advantages of Voltage-based	*Relative Advantages of Charge-based*
• No voltage drop in most cases	• Satisfactory sensor-less performance
• No limits in operating area	• No need to complex nonlinear controllers or models • Implementable as an analogue circuit

Charge-based control systems do not include a position sensor while retaining accuracy. This is often considered as an advantage, as position sensors are costly and occasionally time-consuming to calibrate and operate particularly in small spaces. Further, charge-based control systems, unlike voltage-based control systems, do not require complex nonlinear control to provide satisfactory performance. Such intricate control systems not only have challenging design procedures, but also can only be implemented with digital processors, adding to implementation complexity. On the other hand, charge-based control systems advantageously can be implemented as analogue circuits and still perform well.

However, hardware-wise, the potential of charge-based control systems for analogue implementation does not necessarily mean more simplicity. In comparison with voltage-based control systems, charge-based ones need an extra sensing element [75]. Moreover, if they are implemented as analogue circuits, an extra voltage amplifier and, at least, an extra resistor parallel with the actuator are also needed [74]. In addition, a portion of excitation voltage is wasted in charge-based methods due to voltage drop. The most serious limitation of the charge-based approach is, however, its relatively limited operating areas. The operating areas, where the charge-position relationship for the piezo actuator is not proportional, are not considered appropriate to use charge-based methods. In addition, low frequency operating areas (e.g. frequencies below 2Hz in [64] and below 5Hz in [63, 75]) do not suit charge-based methods. Voltage-based methods, on the other hand, can be designed and used for all operating areas.

Conclusions

This chapter introduced piezo-actuated micro/nanopositioners, the systems, which exhibit controlled position at the micro/nanometre scale. In addition, the contribution of these systems to biodiversity of our eco system and sustainability of manufacturing sector was presented.

Piezo-actuated micro/nanopositioning, through enhancement of cell manipulation, has created significant advancements in assisted reproduction and somatic cell nuclear transfer. These techniques are increasingly used to raise the population of threatened animal species and save them from extinction. It is believed that such technologies are essential to help species in extremis, and any future habitat restoration depends upon progress in these technologies.

In addition, piezo-actuated micro/nanopositioners are progressively employed as a core component of add-on accuracy increasing systems (AAISs). These systems, with minor changes, can considerably improve the performance of outdated machine tools. This is a substantial contribution to sustainable manufacturing, knowing that all existing alternatives lead to huge waste of materials and energy. Without piezo-actuated AAISs, outdated machine tools are either disposed off or their major parts are replaced as otherwise they would witness a significant decrease in product quality and increase in energy consumption. Moreover, piezo-actuated micropositioners play an essential role in vibration-assisted machining, which results in considerable decrease in consumed energy and an increase in machine life span.

The chapter also introduced the triple major components of a piezo-actuated micro/nanopositioner: actuator, control system and sensor, where the latter does not exist in sensor-less micro/nanopositioners. The chapter highlights some shortcomings in this area of technology. As an instance, all methods of both prevalent control approaches, voltage-based and charge-based, suffer from significant drawbacks. Voltage-based methods still struggle to identify and control an intricate nonlinear dynamic system, and charge-based methods are unable to perform in low frequency operating areas. A hybrid method to appropriately function over the entire operating area is yet to be developed. Due to the increasingly important role of piezo-actuated micro/nanopositioning systems in preservation of biodiversity and in sustainability of manufacturing further investments on technology development in piezo-actuated micro/nanopositioning is highly recommended.

References

1. Tang, H., Zeng, Z., Gao, J., and Zhang, X. (2015) A flexible parallel nanopositioner for large-stroke micro/nano machining, *International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO)*, 107-110
2. Li, X. & Cheah, C. (2015) Robotic cell manipulation using optical tweezers with unknown trapping stiffness and limited FOV, *IEEE/ASME Transactions on Mechatronics, 20*(4), 1624-1632
3. Clayton, G. M., Tien, S., Leang, K. K., Zou, Q., and Devasia, S. (2009) A review of feedforward control approaches in nanopositioning for high-speed SPM, *Journal of Dynamic Systems, Measurement, and Control, 131*061101
4. Saedi, S., Mirbagheri, A., Jafari, A., and Farahmand, F. (2014) A local hybrid actuator for robotic surgery instruments, *International Journal of Biomechatronics and Biomedical Robotics 3*(2), 100-105
5. Ghodsi, M., Saleem, A., Özer, A., Bahadur, I., Alam, K., Al-Yahmadi, A., *et al.* (2016) Elimination of thermal instability in precise positioning of Galfenol actuators, *Behavior and Mechanics of Multifunctional Materials and Composites 9800*980008
6. Protopopov, V. (2014) Beam Alignment and Positioning Techniques in Practical Opto-Electronics,(eds., Springer, 309-334
7. Mohammadzaheri, M. & AlQallaf, A. (2017) Nanopositioning systems with piezoelectric actuators, current state and future perspective, *Science of Advanced Materials, 9*(7), 1071-1080
8. Bazghaleh, M., Grainger, S., Mohammadzaheri, M., Cazzolato, B., and Lu, T.-F. (2013) A novel digital charge-based displacement estimator for sensorless control of a grounded-load piezoelectric tube actuator, *Sensors and Actuators A: Physical*,
9. Roshandel, N., Soleymanzadeh, D., Ghafarirad, H., and Koupaei, A. S. (2021) A modified sensorless position estimation approach for piezoelectric bending actuators, *Mechanical Systems and Signal Processing, 149*107231
10. Lovejoy, T. E., Hannah, L., and Wilson, E. O. (2019) Biodiversity and Climate Change: Transforming the Biosphere, Yale University Press

11. Supple, M. A. & Shapiro, B. (2018) Conservation of biodiversity in the genomics era, *Genome biology, 19*(1), 1-12
12. Presicce, G. (2020) Reproductive Technologies in Animals, Academic Press
13. Sansinena, M. (2020) Assisted reproductive biotechnologies in the horse in Reproductive Technologies in Animals,(eds., Elsevier, 13-30
14. Yoshida, N. & Perry, A. C. (2007) Piezo-actuated mouse intracytoplasmic sperm injection (ICSI), *Nature Protocols, 2*(2), 296-304
15. Salamone, D. F., Canel, N. G., and Rodríguez, M. B. (2017) Intracytoplasmic sperm injection in domestic and wild mammals, *Reproduction, 154*(6), F111-F124
16. Zander-Fox, D., Lam, K., Pacella-Ince, L., Tully, C., Hamilton, H., Hiraoka, K., *et al.* (2021) PIEZO-ICSI increases fertilization rates compared with standard ICSI-A prospective cohort study, *Reproductive BioMedicine Online,*
17. Iqbal, A., Ping, J., Ali, S., Zhen, G., Kang, J. Z., Yi, P. Z., *et al.* (2021) Conservation of endangered species through somatic cell nuclear transfer (SCNT), *Conservation Genetics Resources,* 1-9
18. Czernik, M., Anzalone, D. A., Palazzese, L., Oikawa, M., and Loi, P. (2019) Somatic cell nuclear transfer: failures, successes and the challenges ahead, *International Journal of Developmental Biology, 63*(3-4-5), 123-130
19. Singh, B., Mal, G., Verma, V., Tiwari, R., Khan, M. I., Mohapatra, R. K., *et al.* (2021) Stem cell therapies and benefaction of somatic cell nuclear transfer cloning in COVID-19 era, *Stem Cell Research & Therapy, 12*(1), 1-16
20. Zhou, Q., Yang, S., Ding, C., He, X., Xie, Y., Hildebrandt, T., *et al.* (2006) A comparative approach to somatic cell nuclear transfer in the rhesus monkey, *Human Reproduction, 21*(10), 2564-2571
21. Boiani, M. Somatic cell nuclear transfer (SCNT) into mouse oocytes using Eppendorf PiezoXpert®,
22. Moon, J., Jung, M., and Roh, S. (2017) Comparison of developmental efficiency of murine somatic cell nuclear transfer protocol, *Journal of Embryo Transfer, 32*(3), 81-86
23. Uhlmann, E., Peukert, B., Thom, S., Prasol, L., Fürstmann, P., Sammler, F., *et al.* (2017) Solutions for Sustainable Machining, *139*(5),
24. Kianinejad, K., Thom, S., Kushwaha, S., and Uhlmann, E. J. P. C. (2016) Add-on error compensation unit as sustainable solution for outdated milling machines, *40*174-178
25. Kianinejad, K., Uhlmann, E., and Peukert, B. (2015) Investigation into energy efficiency of outdated cutting machine tools and identification of improvement potentials to promote sustainability, *Procedia CIRP, 26*533-538
26. Uhlmann, E. & Kianinejad, K. (2013) Investigation of the upgrading potentials of out-of-date cutting machine tools to promote sustainable and global value creation, *Proceeding of the 11th global conference on sustainable manufacturing,* 574-579
27. Singh, H. & Joshi, R. (2016) Piezoelectric transducer based devices for development of a sustainable machining system-A review,
28. Joshi, R. S. & Singh, H. (2011) Piezoelectric transducer based devices for development of a sustainable machining system-A review, *2011 International Symposium on Applications of Ferroelectrics (ISAF/PFM) and 2011 International Symposium on Piezoresponse Force Microscopy and Nanoscale Phenomena in Polar Materials,* 1-4

29. Zheng, L., Chen, W., and Huo, D. (2020) Review of vibration devices for vibration-assisted machining, *The International Journal of Advanced Manufacturing Technology, 108*1631-1651
30. Minase, J., Lu, T.-F., Cazzolato, B., and Grainger, S. (2010) A review, supported by experimental results, of voltage, charge and capacitor insertion method for driving piezoelectric actuators, *Precision Engineering, 34*(4), 692-700
31. Aggrey, P., Salimon, A., and Korsunsky, A. (2020) Diatomite inspired nanostructured quartz as a piezoelectric material, *Limnology and Freshwater Biology,* 828-829
32. Yang, X., Li, Z., Fei, C., Liu, Y., Li, D., Hou, S., *et al.* (2020) High frequency needle ultrasonic transducers based on Mn doped piezoelectric single crystal, *Journal of Alloys and Compounds, 832*154951
33. Sabek, W., Al-mana, A., Siddiqui, A. R., Assadi, B. E., Mohammad-khorasani, M., Mohammadzaheri, M., *et al.* (2015) Experimental Investigation of Piezoelectric Tube Actuators Dynamics, *2nd International Conference on Robotics and Mechatronics,*
34. Chopra, I. (2002) Review of state of art of smart structures and integrated systems, *Aiaa Journal, 40*(11), 2145-2187
35. Rios, S. & Fleming, A. (2014) Control of Piezoelectric Benders Using a Charge Drive, *Proc. Actuator,*
36. Zhang, X. L., Tan, Y. H., Su, M. Y., and Xie, Y. Q. (2010) Neural networks based identification and compensation of rate-dependent hysteresis in piezoelectric actuators, *Physica B-Condensed Matter, 405*(12), 2687-2693
37. Hussain, F., Khesro, A., Lu, Z., Wang, G., and Wang, D. (2020) Lead free multilayer piezoelectric actuators by economically new approach, *Frontiers in Materials, 7*
38. PiezoDrive. (2021). *Piezoelectric Actuators*. Available: https://www.piezodrive.com/actuators/
39. Ahmadpour, H., Mohammadzaheri, M., Emadi, M., Ghods, V., Mehrabi, D., and Tafreshi, R. (2015) Neural Modelling of a Piezoelectric Actuator Inspired by the Presiach Approach, *International Conference on Artificial Intelligence, Energy and Manufacturing Engineering*
40. Wang, G., Zhao, Z., Tan, J., Cui, S., and Wu, H. (2020) A novel multifunctional piezoelectric composite device for mechatronics systems by using one single PZT ring, *Smart Materials and Structures, 29*(5), 055027
41. Ceramics, P. (2021). *Stack Actuators*. Available: https://www.piceramic.com/en/products/piezoceramic-actuators/stack-actuators/
42. Mohammadzaheri, M., Grainger, S., and Bazghaleh, M. (2013) A system identification approach to the characterization and control of a piezoelectric tube actuator, *Smart Materials and Structures, 22*(10), 105022
43. Moheimani, S. O. R. & Yong, Y. K. (2008) Simultaneous sensing and actuation with a piezoelectric tube scanner, *Review of Scientific Instruments, 79*(7),
44. Mohammadzaheri, M., Grainger, S., Kopaei, M. K., and Bazghaleh, M. (2013) IMC-based Feedforward Control of a Piezoelectric Tube Actuator, *IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing,*
45. Habibullah, H. (2020) 30 years of atomic force microscopy: creep, hysteresis, cross-coupling, and vibration problems of piezoelectric tube scanners, *Measurement, 159*107776

46. Abramovitch, D. Y., Andersson, S. B., Pao, L. Y., and Schitter, G. (2007) A tutorial on the mechanisms, dynamics, and control of Atomic Force Microscopes, *American Control Conference,* 965-979
47. Moheimani, S. O. R. (2008) Invited Review Article: Accurate and fast nanopositioning with piezoelectric tube scanners: Emerging trends and future challenges, *Review of Scientific Instruments, 79*(7), 071101
48. Mohammadzaheri, M., Tafreshi, R., Mohammad-khorasani, M., Bazghaleh, M., and Grainger, S. (2015) Evaluation of the induced voltage in driven electrodes of piezoelectric tube actuators for sensorless nanopositioning, *IEEE 8th GCC Conference and Exhibition (GCCCE),* 1-5
49. Piezo.com. (2021). *Introduction to Piezos*. Available: https://piezo.com/pages/introduction-to-piezos
50. Ceramics, P. (2021). *Piezo Bender Actuators*. Available: https://www.piceramic.com/en/products/piezoceramic-actuators/bender-actuators/
51. Ghodsi, M., Modabberifar, M., and Ueno, T. (2011) Quality factor, static and dynamic responses of miniature galfenol actuator at wide range of temperature, *International Journal of Physical Sciences, 6*(36), 8143-8150
52. Group, V. P. *Strain Gage Instrumentation, Micro-Measurements*. Available: http://www.vishaypg.com/docs/50002/50002.pdf
53. PiezoDrive. *Strain Gauge Position Measurement Systems*. Available: https://www.piezodrive.com/actuators/
54. Akbari, H. & Kazerooni, A. (2018) Improving the coupling errors of a Maltese cross-beams type six-axis force/moment sensor using numerical shape-optimization technique, *Measurement, 126*342-355
55. Rerkratn, A., Luangpol, A., Petchmaneelumka, W., and Riewruja, V. (2020) Position signal detector for linear variable differential transformer, *Energy Reports, 6*603-607
56. electronicspecifier, e. https://www.electronicspecifier.com/products/communications/lvdt-range-suitable-for-high-frequency-response,
57. OMEGA, O. https://www.omega.com/en-us/control-monitoring/motion-and-position/displacement-transducers/ld500/,
58. KEYENCE, K. https://www.keyence.co.uk/products/measure/laser-1d/lk-g5000/,
59. Omidi, E. & Mahmoodi, S. N. (2016) Vibration control of collocated smart structures using H∞ modified positive position and velocity feedback, *Journal of Vibration and Control, 22*(10), 2434-2442
60. "Fiber Optic Displacement Sensors," Philtec, Ed., ed, 2019.
61. Ghodsi, M., Ueno, T., Teshima, H., Hirano, H., Higuchi, T., and Summers, E. (2007) "Zero-power" positioning actuator for cryogenic environments by combining magnetostrictive bimetal and HTS, *Sensors and Actuators A: Physical, 135*(2), 787-791
62. MicroSense. *Precision Capacitive Sensor*. Available: http://www.microsense.net/products-position-sensors.htm
63. Mohammadzaheri, M., Emadi, M., Ghodsi, M., Jamshidi, E., Bahadur, I., Saleem, A., *et al.* (2019) A variable-resistance digital charge estimator for piezoelectric actuators: An alternative to maximise accuracy and curb voltage drop, *Journal of Intelligent Material Systems and Structures, 30*(11), 1699-1705

64. Mohammadzaheri, M., Emadi, M., Ghodsi, M., Bahadur, I. M., Zarog, M., Saleem, A. J. I. J. o. A. I., *et al.* (2020) Development of a Charge Estimator for Piezoelectric Actuators: A Radial Basis Function Approach, *International Journal of Artificial Intelligence and Machine Learning, 10*(1), 31-44
65. Bazghaleh, M., Mohammadzaheri, M., Grainger, S., Cazzolato, B., and Lu, T. F. (2013) A new hybrid method for sensorless control of piezoelectric actuators, *Sensors and Actuators A: Physical, 194*25-30
66. Mousavi Lajimi, S. A. & Friswell, M. I. (2020) Design, analysis, and feedback control of a nonlinear micro-piezoelectric–electrostatic energy harvester, *Nonlinear Dynamics, 100*3029-3042
67. Miri, N., Mohammadzaheri, M., and Chen, L. (2013) A comparative study of different physics-based approaches to modelling of piezoelectric actuators, *The IEEE/ASME International Conference on Advanced Intelligent Mechatronics,*
68. Mohammadzaheri, M., Ziaeifar, H., Bahadur, I., Zarog, M., Emadi, M., and Ghodsi, M. (2019) Data-driven Modelling of Engineering Systems with Small Data, a Comparative Study of Artificial Intelligence Techniques, *5th Iranian Conference on Signal Processing and Intelligent Systems (ICSPIS),*
69. Mohammadzaheri, M., Grainger, S., and Bazghaleh, M. (2012) A comparative study on the use of black box modelling for piezoelectric actuators, *The International Journal of Advanced Manufacturing Technology, 63*1247-1255
70. Mohammadzaheri, M., Grainger, S., and Bazghaleh, M. (2012) Fuzzy Modeling of a Piezoelectric Actuator, *International Journal of Precission Engineering and Manufacturing, 13*(5), 663-670
71. Mohammadzaheri, M., Grainger, S., Bazghaleh, M., and Yaghmaee, P. (2012) Intelligent modeling of a piezoelectric tube actuator, *International Symposium on Innovations in Intelligent Systems and Applications (INISTA),*
72. Ahmed, K. & Yan, P. (2021) Modeling and Identification of Rate Dependent Hysteresis in Piezoelectric Actuated Nano-Stage: A Gray Box Neural Network Based Approach, *IEEE Access, 9*65440-65448
73. Miri, N., Mohammadzaheri, M., Chen, L., Grainger, S., and Bazghaleh, M. (2013) Physics-Based Modelling of a Piezoelectric Actuator Using Genetic Algorithm, *IEEE Symposium on Industrial Electronics and Applications (ISIEA),*
74. Bazghaleh, M., Grainger, S., Mohammadzaheri, M. J. J. o. I. M. S., and Structures (2018) A review of charge methods for driving piezoelectric actuators, *Journal of Intelligent Material Systems and Structures, 29*(10), 2096-2104
75. Mohammadzaheri, M., AlSulti, S., Ghodsi, M., Bahadur, I., and Emadi, M. (2021) Assessment of capacitor-based charge estimators for piezoelectric actuators, *2021 IEEE International Conference on Mechatronics (ICM),* 1-6