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Survey of Motion Actuators for Micro/Nano Positioning Systems

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***Abstract*—In the current evolving arena of science and engineering, slowly the nanotechnology is becoming part and parcel of manufacturing, analysis, testing and verification domains. This has lead to the emphasis on the design and development of systems which have nanometer precision positioning capability with a comparatively long travel range in the order of several centimeters. For such systems, selection of actuators plays a vital role. This paper surveys the various actuators that are commercially available for use in micro/Nano positioning systems.**

***Index Terms*—Micro/Nano actuators, precision positioning, electromagnetic actuators, permanent magnet actuators, piezo electric effect actuators, magnetostriction actuators, SME actuators, MEMS actuators.**

I. INTRODUCTION

Nanotechnology is the study of understanding and manipulation of matter on an atomic scale, which is in the dimensions of less than 100nm [1]. Drexler described machines like motors, robot arms and computers on the molecular scale. Nano scale materials were used for centuries, one of the earliest applications was use of gold and silver particles to create colour stained glass windows for medieval churches [2]. Today nanotechnology can be used in most of the industrial domains like electronics, communication, material science, physics, chemistry and bioengineering to name a few. With the increasing applications in varied domains, there is an increased demand for accuracy and precision positioning technologies. Ultra precision positioning is the heart of design of nanotechnology based devices. The ultra precision positioning technologies are widely used in

- Scanning tunnelling microscope and atomic force microscope which are widely used in biology, chemistry and material science.
- In the fabrication of integrated circuits for positioning of wafers and mask alignment.
- In biotechnology, it is used for cell tracking and manipulation, DNA analysis.
- In material science for manipulating and testing nano materials.

Currently ultra precision positioning devices with a range of less than centimetres and with an accuracy of nanometre are a must prerequisite for nanotechnology. The orientation of the review is to know the current state of arts of actuators for micro/nano positioning systems. The review has been made considering the actuators availability in the current market scenario. For the development of a precision positioning system, the market availability of actuators is more important than considering the actuators which are still in the

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research or prototype stages.

II. Ultra Precision Positioning Devices

Motion devices i.e., actuators with a range of micro/nano scale are widely used for achieving ultra precision positioning. The main goal is to produce a long travel range motion based on the input, with a high accuracy and precision. These actuators can be broadly classified as

A. Electromagnetic Based Actuators

In this class of actuators, either the stator or the rotor consists of a current carrying coil. This current carrying coil electromagnetize's the stator or rotor and causes the motion in the actuator. The most commonly used electromagnetic actuators for precision positioning applications are stepper and DC motors.

Stepper Motor: Stepper motors are non linear actuators that translate electric input into motion [3]. The stepper motors are operated in either of the following modes: a) Full wave mode (FWM), b) Half wave mode (HWM) and c) Microstep mode (MSM). Considering the motor specification of fifty teeth and four poles, the FWM has a resolution or step angle of 1.8O, while HWM has a resolution or step angle of 0.9O. The practical limit on minimum step angle that may be attained in MSM depends on the physical dimensions of the stepper motor. For example we can achieve a resolution of MSM can have 0.05625O as resolution or 1/32 of one full step angle (1.8O). Since the paper is concerned about the low resolution actuators, stepper motors in MSM mode are considered for the discussion; let us comprehend the principle of operation of MSM. In this mode, each full step (i.e., 1.8O) is split into a number of steps, called microsteps by applying suitable electric signals to the motor poles. The electric signals are sinusoidal pulse width modulated and are in quadrature phase with each other.

The merits of the stepper motors are:

- If the motor poles are energised, and even though stepper motor is not rotating it can still bear full torque [4].
- Error does not sum up from one step to next step, resulting in precision in positioning [5].
- Latency between the changing of rotation direction, starting – stopping of rotation and the application of the corresponding input electric signals is minimal.
- Motor controller design is comparatively simpler than the other electromagnetic based actuators.
- The demerits of the motor are [6]:
- Vibrations are generated during the course of motor operation, mainly because of the discrete or step movement of the motor.
- Very high speed operation is difficult to achieve.

The minimum resolution that can be achieved by using a stepper motor depends on the physical dimensions of the stepper motor and the controller design. The controller is an electronic circuit which generates suitable electric signals for dividing a full step into micro steps. There are commercially available stepper motor based products that has a travel range of 50mm, with a maximum velocity of 20 mm/s and a resolution less than 500nm. This is accomplished using a stepper motor having 1.8O full step, and 4, 09,600 micro steps per 1 mm of translation [7].

DC Motors: It is an actuator which converts the applied DC voltage into a rotational motion. The rotation of the DC motor is continuous and smooth when compared to the stepper motors. For use of the motor for positioning applications, the DC motor is used along with efficient controllers, position and speed sensors.

The merits of DC motor are [8]:

- The speed of the motor can be varied in a wide range.
- The motor can be used in applications having heavy loads, since the DC motor has a large starting torque.
- The torque can be maintained constant over a wide range of speed values.

The demerits of the motor are [8]:

- DC motor with brushes results in increased maintenance cost not to forget the EMI/RF interference and electric shock.
- The heat generated during the operation of the motor is significantly high; this can be cause of concern when operating at nano scale.
- To maintain position, an external brake has to be utilized or constant power is to be applied.

There are controllers which can achieve a resolution of 0.016 µm, which translates into minimum angle change that can be achieved for a rotating motor is 0.175O. The sensor used for the positional accuracy has a sensor resolution of 2048 counts per revolution. There are commercially available DC motor based products that has a maximum travel range of 50mm, with a maximum velocity of 2.6 mm/s [9].

B. Permanent Magnet Based Actuators

These actuators operation is based on the theory that when a current carrying conductor is placed in a magnetic field a force is generated. A permanent magnet is used for the generation of magnetic field. The most commonly used actuators of this category for positioning applications are permanent magnet synchronous motor and voice coil motor.

Permanent Magnet Synchronous Motor: This actuator is similar to an induction motor (3 phase), except that in this actuator the rotor consists of a permanent magnet rather than being electro magnetised. Since it is a 3 phase motor, three sinusoidal waves which are accurately 900 phase apart are applied as input. Once the magnetic field of the rotor is synchronized with the magnetic field of the stator, the rotation is generated because of the varying sinusoidal flux of the stator. By using appropriate electronic control techniques, the permanent magnet synchronous motors can be used for position control applications.

The motor has merits of [10]:

- Continuous, smooth rotation without any ripples.
- High speeds of rotation can be achieved.
- Since it does not have any wear and tear brushes, low maintenance cost and high efficiency is achieved.
- Electro-magnetic interference is low.
- Precise control over the speed can be achieved without any requirement of a sensor.

The demerits include [10]:

- Complexity of design and construction because of the use of multiple magnetic fields and delicate magnets.
- Complex driver and controller design.
- Use of magnetic field hinders its use in embedded hardware.
- The cost of the actuators is high.

Commercially available actuators have maximum speed of 12,000 revolutions per minute with a resolution of 0.010, which is achieved by using an encoder with 32,768 positions per revolution capability [11].

Voice Coil Motor: It is a simple actuator which operates on the Lorentz Force Principle. Whenever a current carrying element is introduced in the magnetic field, a force acts on the coil. The direction and magnitude of the force depends on the direction and magnitude of the current in the coil. The actuator consists of a simple permanent magnet (N and S poles), between which an axial current carrying coil is placed. Precise position can be achieved by controlling the current in the coil and using position encoders or sensors [12].

The merits of the actuator include [13]:

- Absence of non linear effects like backlash.
- High speed operation is possible.
- By using an encoder, high accuracy and repeatability of operation can be achieved.
- Simple design and construction.
- Noiseless operation.

The actuator suffers from the following demerits [13]:

- Has low force to weight ratio.
- Current is required even while in holding phase.
- Complex design and additional components are required when the actuator has to move mass vertically.
- Suitable compensation is required for countering back electromotive force.

Commercially available actuators have a resolution of 1.02 mm with a total travel range of 12.7 mm [14].

C. Piezo Electric Effect Based Actuators

These actuators make use of the inverse piezoelectric effect, i.e., the physical deformations due to applied electric field are used to produce a linear or rotary motion. The most commonly used actuators for ultra precision position applications are PZT actuators, inchworm actuators and ultrasonic actuators.

PZT Actuators: These actuators convert electric energy into motion and no magnetic field property is utilised to produce motion [15]. In certain crystals, electric field is produced when stress is applied. This is known as the piezo electric effect. The inverse effect is when electric field is applied they undergo physical deformation. This deformation is used to produce motion in PZT actuators [16]. The most commonly used crystal is lead zirconate titanate [17].

The merits of the PZT actuators are [18]:

- No moveable components; motion is produced only by physical deformation and hence there are no wear and tear of components; leading to low maintenance cost.
- No magnetic field and hence do not interfere with any other electronic components.
- Very high resolution and accuracy in the motion in nano meter scale.
- A single actuator can be used large number of times without any damage to the crystal.
- Very low amount of power is consumed while actuator produces motion; when the actuator is in standstill it does not require any power.

The demerits of the actuator are [18]:

- Has a very small travel range.
- Suffers from non linear effects like hysteresis and creep.

There are PZT actuator based commercial products which have a maximum travel range of up to 1mm, with a resolution

Of up to 0.5nm. Resolution increases with decrease in travel range [19].

Inchworm Actuator: Inchworm actuator uses three PZT elements to produce motion [20]. The actuator consists of two outer clamps (1 and 3), and a central PZT element (2) as illustrated in the figure 1. The three elements are mounted on a shaft. The principle of operation of the actuator is based on the principle of friction with small payload. When an electric field is applied to the PZT element it expands and contracts. When electric field is applied to clamp1, it holds the shaft, now if input is applied to the PZT element it expands. After the required length or the maximum length of the PZT is reached, electric field is applied to clamp 3, so that it holds on to the shaft. The electric field from the clamp1 is removed, so that it unclamps from the shaft. By reducing the input to a minimum value to the PZT element, it contracts. After contraction, again electric field is applied to clamp1, so that holds on to the shaft. These steps are repeated to travel along the length of the shaft. Power is required to hold on to a position and the actuator does not produce heat when holding onto a position, thus minimizing the effects of thermal drift. The actuator has a nano meter step resolution with a travel range of hundreds of microns.

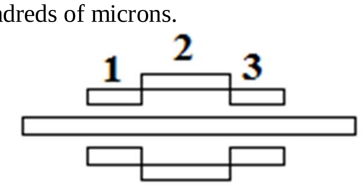

Figure 1. Basic representation of inchworm actuator [21]

The actuator shares all the merits of the PZT actuator; in addition it overcomes the travel range limitation of the generic PZT actuator. The demerits of the actuator are [22]:

- Slow response.
- High input electric field is required.
- Principle of operation is based on friction and hence prone to wear and tear.

Commercially available actuators can have a travel range of 203.2 mm with resolution of 4 nm with an operational speed of about 2 mm/s [23].

Ultrasonic Actuator: In ultrasonic actuators, motions are produced due to the ultrasonic vibrations in the actuator. The basic principle of operation of these actuators is the amplification of the stator vibration at resonance frequency. The rotor in contact with the stator starts to actuate because of friction between the stator and rotor [24].

The merits of the ultrasonic actuator are [25]:

- Fast response to the applied input.
- High torque at low actuation speed.
- High torque to weight ratio.

- Noiseless operation.
- No power is required when the actuator is not in motion and is in holding state.
- Magnetic field is not generated.

Some of the notable demerits are [25]:

- Actuator gets heated due to friction.
- Actuator has low life time.
- Requires complex driver and control techniques.

Commercially available ultrasonic actuators have a travel range of 50 mm, for a minimum resolution of 10 µm at a velocity of 200 mm/s [26].

D. Magnetostriction property based actuators

These actuators make use of the magnetostriction property, i.e., the physical deformations due to applied magnetic field are used to produce a linear or rotary motion. The most commonly used actuator for positioning applications is magnetostrictive actuator.

These actuators are analogous to the PZT actuators. Materials like Terefenol-D and Metglass [27], produce a physical length change when they are under the influence of magnetic field. The vice versa also holds good.

This property is known as the magnetostriction property and this property is exploited in the magnetostrictive actuators. The basic principle of operation is magnetostrictive material is placed within the electromagnetic coil. By controlling the current flowing through the coil, the magnetic field and hence the variation length of the material is controlled. This variation in length is utilized for producing actuation.

The merits of magnetostrictive actuators are [28]:

- Large force is generated during actuation.
- Absence of contacts or brushes, hence the actuator has a large lifetime.
- Requires low electric input.
- The actuators have a high energy density.

The demerits of the actuators are [28]:

- Low availability of magnetostrictive materials.
- With the presence of magnetic field; precaution required while interfacing with large complex circuitry.
- These actuators are expensive because of the limited availability of the magnetostrictive materials.

Commercially available actuators can have a travel range of 200 mm, with a resolution of 2 µm [29].

E. Shape Memory Effect Based Actuators

There are certain class of alloys, which can remember their shape. At a particularly high temperature the alloy is made to take any required shape. When the temperature of the alloy cools down, if the alloy's shape is deformed to any other shape, it will get back to the original shape when the alloy is heated. This phenomenon is called shape memory effect (SME) and these alloys are called Shape Memory Alloys' (SMA). The most commonly used alloys for SMA applications are copper zinc aluminium alloy (CuZnAl) and nickel titanium (NiTi) [30]. One important application of SMAs' is actuator. In SMA Actuator, rapid heating and cooling of SMA wire produces the required motion [31].

The merits of the actuator are [32]:

- Noiseless operation.
- SMA materials are defiant to corrosion and are compatible to bio-materials.
- It has a very high value of force to weight ratio.
- Simple actuator design consisting of `the SMA material, heating and cooling systems.

The demerits of the actuator are [32]:

- Speed of operation is limited by heating and cooling operations.
- Low efficiency.
- Depends on the operational environment.
- Non linear characteristics and effects.
- As of now SMA materials are expensive.

Commercially available actuators having SMA of diameter of 0.127 mm can produce a resolution of 0.3429 mm with a travel range less than 28.575 mm, operating at low voltage (less than 9 volts) and requires less than 1 sec for heating and cooling [33].

F. MEMS Based Actuators

The success of micro electro-mechanical systems (MEMS), has led to the development of various actuators and sensors. There are various actuators, they can be classified as: Electrostatic, Thermal and Magnetic [34]. MEMS based electrostatic actuators, in essence consists of a stator and a movable shuttle. Electric field is applied between the stator and the shuttle to generate actuation. MEMS based thermal actuators consists of two arms, and the difference in thermal expansion between the two arms results in actuation. In MEMS magnetic actuators, the actuation is a result of the applied magnetic field. Magnetic field can be generated either by applying external field or electromagnetic or magnetic relay. The MEMS based actuators are having a position resolution of about 5nm [35] and a maximum travel range of 1-100 µm [36].

When compared with the other actuators, MEMS actuators have lower maximum force capability. The achievable resolution for MEMS force sensors goes down to 10−11 N, while the maximum measurable force is approximately 10 N [37]. Development of MEMS based actuators is still in the investigation phase.

III. Conclusion

There are various parameters which should be considered while selecting an actuator for a specific application. When considering the applications involving precision positioning, two most important parameters resolution (also called the stroke) and the travel ranges are of primary concerns. Various merits and de-merits of an actuator also play an important role, like suitability for embedded applications, electromagnetic interference effect, design and development of driver and controller circuits and not to forget the cost of the actuators. From the detailed study the selection of actuators bases on accuracy can be made as follows:

Table I: Comparisons of Different Actuators

Rank	Actuator	Resolution	Travel Range
1.	PZT actuator	0.5 nm	1 mm
2.	Inch worm actuator	4 nm	203.2 mm
3.	MEMS Based actuators	5 nm	0.1mm
4.	DC motor	16 nm	50 mm
5.	Stepper motor	<500 nm	50 mm
6.	SMA actuator	2000 nm	<28.575mm

Longer travel range and precise positioning in the range of nanometer requires development of a hybrid system consisting of a long travel range actuator with an actuator of resolution in the nanometer range. Considering availability and cost, inchworm actuator, DC motor or stepper motor can be utilized for long range travel; for final precision positioning PZT actuator can be used.

References

[1] Roger W. Whatmore, 'Nanotechnology—what is it? Should we be worried?', Occupational Medicine Journal (London) , August 2006, Volume 56, Issue 5, pp-295-299.

[2] Colomban, Philippe. "The use of metal nanoparticles to produce yellow, red and iridescent colour, from Bronze Age to present times in lustre pottery and glass: solid state chemistry, spectroscopy and nanostructure.", Journal of Nano Research 8 (2009): 109-132.

[3] Paul E. Sandin, Robot Mechanisms and Mechanical Devices Illustrated, McGraw-Hill/TAB Electronics; 1 edition (June 27, 2003)

[4] Jack R Smith, 'Programming the PIC Microcontroller with MBASIC', Illustrated Edition 2005, Newness Publisher, ISBN 0750679468,9780750679466

[5] V V Athani, 'Stepper Motor: Fundamentals, Applications And Design', 1997 Reprint Edition, New Age International Publisher, ISBN 8122410065, 9788122410068

[6] Mahalik, 'Mechatronics: Principles, Concepts and Applications', Tata McGraw Hill Education, 2003, ISBN 0070483744, 9780070483743

[7] THORLABS, 2" (50 mm) Motorized Actuators: DC Servo & Stepper Motors, www.thorlabs.com

[8] Chang-liang Xia, 'Permanent Magnet Brushless DC Motor Drives and Controls', John Wiley & Sons, 2012, ISBN: 1118188357, 9781118188354

[9] PI M-235: High- Resolution Linear Actuator with DC Motor, www.physikinstrumente.com

[10] Overview-Permanent Magnet Synchronous Motors, http://www.freescale.com

[11] Permanent Magnet AC Synchronous motors, www.bonfigliolidobrasil.com.br

[12] Bill Black, Mike Lopez and Anthony Morcos, “Basics of Voice Coil Actuators”, http://acm-magnetics.com
[13] Wavre, N. & Thouvenin, X., “Voice-coil actuators in space”, Sixth European Space Mechanisms and Tribology Symposium, Proceedings of the conference held 4-6 October, 1995 in Zürich, Switzerland. Edited by W.R. Burke. ESA SP-374. European Space Agency, 1995., p.227
[14] Voice Coil Actuator, www.beikimco.com
[15] Chandratreya S. S., Fulrath R. M. and Pask J. A., “Reaction Mechanisms in the Formation of PZT Solid Solutions”, Journal of the American Ceramic Society, July 1981, Volume 64, Issue 7, pp- 422–425.
[16] Jaffe, Bernard. ‘Piezoelectric ceramics’. Vol. 3. Elsevier, 2012.
[17] Chen, San-Yuan, and I-Wei Chen. "Temperature–Time Texture Transition of Pb (Zr1− xTix) O3 Thin Films: I, Role of Pb-rich Intermediate Phases." Journal of the American Ceramic Society, Volume 77.9 (1994),pp- 2332-2336.
[18] Goldfarb, M., and Nikola Celanovic. “A lumped parameter electromechanical model for describing the nonlinear behaviour of piezoelectric actuators”, Journal of dynamic systems, measurement & control, Volume 119, Issue 3-1997, pp478-485.
[19] Physik Instrumente, P-602 PiezoMove Flexure Actuator with High Stiffness, www.physikinstrumente.com
[20] Rennex, Brian G. ‘Inchworm actuator’, U.S. Patent No. 5,332,942. 26 Jul. 1994.
[21] Marek Novotny, Pekka Ronkanen, Tampere University of Technology, ' Piezoelectric Actuators', www.ac.tut.fi
[22] Mark Vaughan, Donald J. Leo, “Integrated Piezoelectric Linear Motor For Vehicle Applications”, Proceedings of IMECE’2002, ASME International Adaptive Structures and Materials Systems Symposium November 17-22, 2002, New Orleans , LA, USA
[23] Burleigh Instruments Inc., MODEL 6000, Inchworm Motor Controller, Instruction Manual.
[24] Ueha, S.; Tomikawa, Y.; Kurosawa, M.; Nakamura, N., 'Ultrasonic Motors: Theory and Applications', Clarendon Press, (December 1993)
[25] Amir Manbachi, Richard S C Cobbold, “Development and application of piezoelectric materials for ultrasound generation and detection”, Ultrasound Journal, November 2011, Volume 19, pp- 187-196,
[26] Linear Shaft Motor Ultrasonic-M272, www.piezo-motor.net
[27] Alison Flatau, Iowa State University, Magnetostrictive Transducers, Actuators, and Sensors, www.public.iastate.edu
[28] J.L. Pons, “A comparative analysis of Piezoelectric and Magnetostrictive actuators in Smart Structures”, Articulo, Boletin De La Sociedad, Espanalade Ceramica y Vidrio, 2005, Volume 44, Issue 3, pp 146-154.
[29] Cedrat Technologies, Magnetostrictive Actuator, www.cedrat-technologies.com
[30] Tadaki, T., K. Otsuka, and K. Shimizu. "Shape memory alloys." Annual Review of Materials Science, Volume 18, Issue 1-1988, pp- 25-45.
[31] Richard Lin, Stanford University, Shape Memory Alloys and Their Applications, www.stanford.edu
[32] Gabriel, Kaigham J., William SN Trimmer, and James A. Walker. 'Shape memory alloy actuator', U.S. Patent No. 4,700,541. 20 Oct. 1987.
[33] Mobi linear shape memory alloy actuator, www.migamotors.com
[34] D J Bell, T J Lu, N A Fleck and S M Spearing, "MEMS actuators and sensors: observations on their performance and selection for purpose", Journal of Micromechanics and Microengineering, 2005, Volume 15, pp-153-164
[35] Santosh Devasia, Evangelos Eleftheriou, and S. O. Reza Moheimani, "A Survey of Control Issues in Nanopositioning", 2007, IEEE Transactions on Control Systems Technology, Volume 15, Issue 5:802-823
[36] Mahalik, Nitaigour Premchand, MEMS, Tata McGraw-Hill Education, 2008.
[37] Wise J D, Rice University, ‘An Introduction to Micromechanical Actuators-A Device Overview and a Specific Application',www.herberts.org