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Micro-motion devices technology: The state of arts review

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Abstract In this paper we review the world-wide study on micro-motion systems both from an academic and an industrial perspective. The objective of the review is to answer the following questions: (1) What are the limitations of technologies to develop a micro-motion device in terms of function, motion range, accuracy, and speed it can achieve? (2) What is any economic implication of these technologies? (3) What are future research directions? The micro-motion systems considered in this paper are classified into four kinds in terms of their motion ranges: (a) < 1 μm, (b) 1 ~ 100 μm, (c) 100 ~ 1000 μm, and (d) > 1000 μm. This review concludes that the PZT actuation element integrated with the compliant mechanism is the most promising technology which can achieve high accuracy (sub-nanometer) of all four kinds of motion ranges. This promise is further based on the amplification technology using the compliant mechanism concept. The amplification mechanism is used to compensate the problem with a limited stroke of the PZT actuation element. The compliant amplification mechanism allows one to achieve a high resolution and high stiffness motion which does not compromise the loss of accuracy due to motion amplification. The PZT actuation element and the compliant mechanism are both economically viable. Future research direction should generally focus on the interface between the PZT actuation element and compliant mechanism and the reliability of the compliant mechanism under cyclic deformation of compliant materials.

Keywords Micro-motion system · Actuator · Compliant mechanism · Manipulator

1 Introduction

A steady need for increased accuracy and precision in production machinery and other devices has led to the development of technologies. Precision engineering emerged from mechanical engineering followed by micro-mechanics and, recently, nanotechnology. The fact of smaller volume per unit alone often opens a new market. Further, the smaller volume per unit enables to combine several functions within one product with an acceptable price and size. On the other hand, the miniaturization of devices enables the development of new functions.

Nowadays, industry is quite interested in using precision manufacturing and assembly for small parts with a size ranging from very few millimeters down to micrometers. Also, there exists a worldwide interest in micro tools. Micro-motion devices that can perform very small motions with very high positioning accuracy potentially have wide application in industry. Typical applications are chip assembly in the semiconductor industry, cell manipulation in biotechnology, and automatic surgery in medicine.

This paper gives a comprehensive review in the area of micro-motion devices. The goal of this review is to update the state of arts of micro-motion systems in both research and development. This means that the review will cover both research results and industrial products. The review will be conducted by classifying the micro-motion systems

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technology into three major systems: (1) actuators, (2) manipulator systems for micro motion, and (3) compliant mechanisms for micro motion. The main goal of actuators for micro motion is to create a linear motion between the input and output signals. The main goal of the manipulator systems for micro motion is to create a non-linear motion between the input and output signals, in addition to a long motion range with small resolution. Finally, the main goal of compliant mechanisms is to provide a relatively new paradigm for generating micro motion.

The objective of the review is to answer the following questions: (1) What are the limitations of technologies to develop a micro-motion device in terms of function, accuracy, and speed it can achieve? (2) What is any economic implication of these technologies? (3) What are future research directions?

The paper is organized such that Sects. 2, 3, and 4 will discuss each of the three major systems in detail. Section 5 reviews most recent technology developments available in industries. Section 6 discusses limitations on each of the systems reviewed in the previous sections, which then derives some future directions of work on the subject of micro-motion systems.

2 Actuators

In recent years, owing to the necessity of reducing the physical size of electronic devices, micro-fabrication techniques have emerged which also make it possible the production of very small mechanical components, including miniature actuators. Smart materials whose characteristics may be made to change rapidly by some external influences are often used to augment the basic actuator movements or coupling forces from one part of a system to another. Generally speaking, two categories of actuators can be distinguished: those working with fields and those changing their shapes. The first category uses forces created by fields such as electrostatic, magnetostatic, and electro-dynamic. Conventional motors such as DC servo motor, AC servo motor, and Stepper motor fall into this category. Among them, the electrostatic force is most attractive to applications in a micro-motion actuator due to its scaling behavior and material requirements. For the electrostatic actuators, only an electrical conducting material is necessary. The second category of actuators generates, primarily, a strain in the material, which can be converted into a force. The piezoelectric (PZT), shape memory alloy (SMA), ultrasonic, inchworm, magnetostrictive, and thermal actuators fall into this category [7]. Here, the characteristics of actuators are dependent on the material properties; which thereby also implies the use of special materials.

2.1 Conventional actuators (steppers and DC motors)

In the optics world, motorized micrometers - or “motor mikes” - integrated into translation or rotation stages have dominated classic motion control. These devices typically consist of a stepper or DC servomotor coupled to a precision screw-and-nut set to create a linear pusher. While DC motors provide smooth continuous motion, steppers rotate in discrete steps in response to electrical pulses.

Stepper motors use the principle of magnetic attraction and repulsion to move a screw. By alternately applying current to the individual windings in the motor stator, a torque is created that turns a permanent magnet and/or iron rotor. When the windings of the stepper motor are energized, a holding torque is generated; the motor moves only when that current is switched from winding to winding. Unlike DC motors, a stepper motor has an inherent holding, detent, or torque that can be used to maintain the position of devices in the power-off state for a period of time. The higher-resolution micro-stepping motors, however, can jump to the nearest full-step location when the power is turned off. Some stepper motors can achieve over 25 mm travel range with 1 μm accuracy. Because steppers provide an inexpensive open-loop method to achieve relatively high accuracy, they have been used in the optics world. Stepper motors, however, are bulky, noisy, generate a significant amount of unwanted heat, and do not provide smooth continuous motion. Moreover, they provide no manual-adjustment capability. The large size of stepper motors also makes them difficult to incorporate into small mechanisms.

DC motors provide smooth, continuous motion as well as high speeds and submicron accuracy when used with an encoder. The bulky DC motor consists of an armature - coils of wire around a metal core - inside a magnetic field. When electric current is applied to the windings, the armature interacts with the magnetic field causing the armature to turn. Because the DC motor requires constant power or an external brake to maintain position, it is not an ideal solution for set-and-hold applications. Moreover, it generates a significant amount of unwanted heat and requires a feedback mechanism for controlling position and velocity. Even when holding a specified position, because of hysteresis, these motors often dither or oscillate around the position.

It is possible to build an accelerator by combining the stepper motor and the DC motor techniques, which is called ferroelectric actuators. Ferroelectric actuators are made with piezoelectric or electrostrictive materials. These are materials that expand and contract in response to the square of an applied electrical voltage. Such a combination allows bringing together the strength of the stepper in terms of its inherent holding function and the strength of the DC motor in terms of its relatively high accuracy (submicron).

Piezos, however, cannot maintain position without the electrical power and they exhibit nonlinearity, creep under power, and hysteresis. Besides, piezos are by themselves used to build actuators - see the following section.

2.2 PZT actuators

The piezoelectric actuator (PZT) is a well-known commercially available device for managing extremely small displacements in the range of 10 pm (1 pm = 10^{-12} m) to 100 μm [1]. A PZT actuator is an electromechanical device that undergoes a dimensional change when voltage is applied. The conversion of electrical energy into mechanical energy takes place without generating any significant magnetic filed or the need for moving electrical contacts. Dimensional changes are proportional to the applied voltage and can therefore be adjusted with extremely high resolution. PZT actuators can be operated over millions of cycles without wear or deterioration. Their high response speed is limited only by the inertia of the object being moved and the output capability of the electronic driver. Piezo actuators offer the following advantages:

- Sub-nanometer resolution
- Large force generation
- Sub-millisecond response
- No magnetic fields
- Extremely low steady state power consumption
- No wear and tear
- Vacuum and clean room compatibility

The holding function of the PZT actuator, which is one of the important requirements for any positioning device, depends on the shape of electronic signals which can be made rather accurate.

The PZT actuator has its disadvantages: highly nonlinear input/output behavior, creep, and hysteresis, as mentioned above. This disadvantage can be, nevertheless, alleviated with advanced modeling and controlling technologies. Another major disadvantage with the PZT actuator is that it has a very small motion range. There are many ways to amplify the displacement by stacking multiple piezoactuators in different configurations. Although modest motion amplification can be achieved through such means, many of such arrangements are cumbersome and impose a heavy penalty of voltage requirements. The length of a piezo stack is limited due to the position error generated at the end of the stack. The stacking is also limited due to the stress generated in the piezo slice.

2.3 SMA actuators

Shape memory alloys (SMA) are a unique class of alloys which are able to "remember" their shape and are able to return to that shape even after being bent. At a low temperature, a SMA can be seemingly “plastically” deformed, but this “plastic” strain can be recovered by increasing the temperature. This is called the shape memory effect (SME). At a high temperature, a large deformation can be recovered simply by releasing the applied force. This behavior is known as superelasticity (SE).

The most widely used shape memory material is an alloy of nickel and titanium called nitinol. This particular alloy has excellent electrical and mechanical properties, long fatigue life, and high corrosion resistance. As an actuator, it is capable of achieving up to 5% strain and 50,000 psi recovery stress, resulting in ~ 1 Joule/gm of work output. nitinol is readily available in the form of wire, rod, and bar stock with transformation temperature in the range of −100° to +100° Celsius. More recent applications of nitinol in micro-electro-mechanical systems (MEMS) have led to the development of nitinol in the form of sputter deposited thin film. Use of SMA is limited by the rate at which the wire can be cooled, and is usually limited to a few hertz at best. This limited cooling rate of the SMA constrains the bandwidth of the controller. Efforts to enhance the cooling rate require much greater levels of power.

2.4 Inchworm actuators

The inchworm actuator (e.g., one from Burleigh Instruments Inc. [66]) uses piezos to achieve the 4 nm resolution with travel ranges up to 200 mm (see Fig. 1). The principle of the Inchworm motor can be described as follows. The outer two elements, numbers 1 and 3, act as clamps. The central PZT element, number 2, expands and contracts along the motor shaft when voltage is applied. Though all three elements operate independently, they operate in a controlled manner in terms of timing of operations. When a voltage is applied to PZT element 1, it clamps the shaft. Then a variable rate staircase voltage is applied to element 2, causing it to change length in discrete steps on the order of nanometers. This motion is directly coupled to the output shaft. The staircase takes hundreds of steps from its upper to lower limit and may be stopped and reversed at any point on the ramp. At the end of the staircase ramp, a voltage is applied to element 3, causing it to grip the shaft. Voltage is removed from element 1, releasing it from the shaft. The staircase starts downward until it reaches its lower limit, at which point element 1 is reactivated, element 3 is released and the staircase begins again. Therefore, a motion range is limited only by the length of the motor shaft.

Three piezo elements move a shaft with a force greater than 15 N. Two clamps and one extension actuator move in a synchronized “clamp-extend-clamp-retract” motor cycle. The motor is also quite fast - typical motor cycles produce >

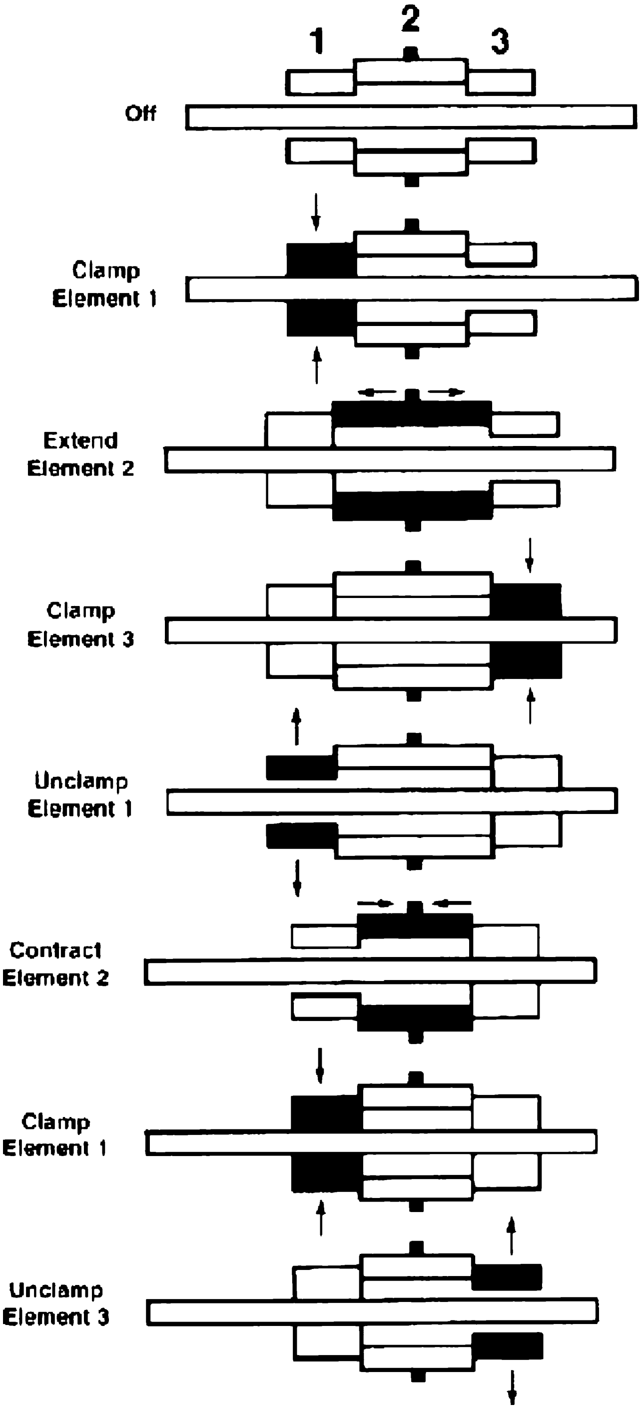

Fig. 1 Inchworms actuators [66]

2 µm of movement which, at a motor frequency of 750 *Hz*, corresponds to a velocity greater than 1.5 mm/s. Power is required to hold the position, but the motor does not produce heat when holding a position, thus minimizing the effects of thermal drift. The limiting factor of the inchworm motor is its friction-based working principle and thus relatively small payload.

2.5 Ultrasonic motors

An ultrasonic motor (USM) is characterized by the absence of noise during operation, with high torque-weight ratio, highly accurate speed, and position control. Ultrasonic motors can be classified by their mode of operation (static or resonant), type of motion (rotary or linear) and shape of implementation (beam, rod, disk). The fundamental principles of solid-state actuation tie them together: microscopic material deformations (usually associated with piezoelectric materials) are amplified through either quasi-static mechanical or dynamic/resonant means. Several of the motor classes have seen commercial applications in areas needing compact, efficient, and intermittent motion. Such applications include: camera auto focus lenses, watch motors, and compact paper handling.

Figure 2 shows an exploded view of a rotary traveling-wave-type USM with its basic components [42]. The general principle of the operation of ultrasonic motors is to generate gross mechanical motion through the amplification and repetition of micro-deformations of active material. The active material induces an orbital motion of the stator at the rotor contact points and frictional interface between the rotor and stator rectifies the micro motion to produce macro motion of the stator. The active material, which is a piezoelectric material, excites a traveling flexural wave within the stator that leads to elliptical motion of the surface particles. Teeth are used to enhance the speed that is associated with the propelling effect of these particles. The rectification of the micro motion of an interface is provided by pressing the rotor on the top of the stator, and the frictional force between the two causes the rotor to spin. This motion transfer operates as a gear to a much lower rotation speed than the wave frequency. The limiting factor

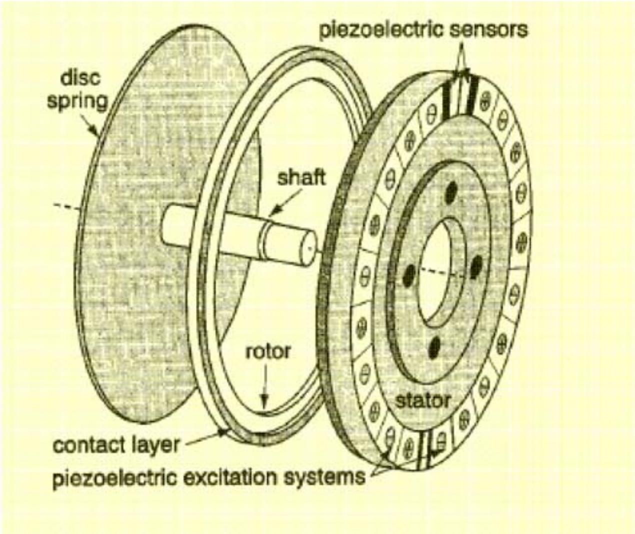

Fig. 2 Rotary traveling-wave-type USM with its basic components (Maas et al. [42])

with the USM appears to be the friction as a part of its working principle.

2.6 Picomotor actuators

Picometer actuator employs piezos in a new manner in its picomotor actuator (The New Focus Inc. [45, 75], Santa Clara, CA). The picomotor - a piezoelectric actuator that turns a screw- allows mounts, stages, and micrometer-replacement actuators to achieve < 0.1 µm resolution with remote control or manual adjustment capability. Figure 3 shows how the picomotor works like your own fingers. Two jaws grasp an 80-pitch screw, and a piezoelectric transducer (piezo) slides the jaws in opposite directions just like your thumb and forefinger would.

Because the piezo is used only to turn the screw and not to hold the adjusted position, the picomotor does not suffer from the typical piezo problems of hysteresis and creep, and can maintain its position with no applied voltage. However, a problem that conventional piezo-driven actuator and picomotors do share is that of repeatability. Although the picomotor does not exhibit hysteresis, small variations in screw rotation from step to step can lead to repeatability errors. These errors are accentuated if the force acting against the picomotor's motion changes throughout its travel, as when moving against a spring. In addition, the friction is a limiting factor for the speed and payload of picomotor.

2.7 Stick-slip actuator

The principle called "stick-slip" is shown in Fig. 4. Stick-slip actuator generates motion by taking advantage of the friction/inertia nature of its components. The friction-inertia nature is explained to facilitate discussion of the stick-slip actuator. There are two objects between which a friction is present, as shown in Fig. 4. In (a) both the objects stay at their initial position. Assume that object 1 moves a step 's0' to the right to arrive at a position; see (b). During this period of time, object 2 moves nearly the same step 's0' to the right because of the static friction (suppose that the friction force is sufficiently large to overcome the inertia of object 2). Note that in (b), object 2 gets accelerated to the right. Suppose that in (b), object 1 moves back to its initial position (a). During this period of time, suppose that the inertia of object 2 is larger than the static friction; therefore a sliding motion occurs between object 1 and object 2, and consequently object 2 reaches its final position (c). The net step movement of object 2 is 's'. In this figure, Δs may be called "step loss". It is noted that the step loss may also happen in (b) where the two objects move to the right.

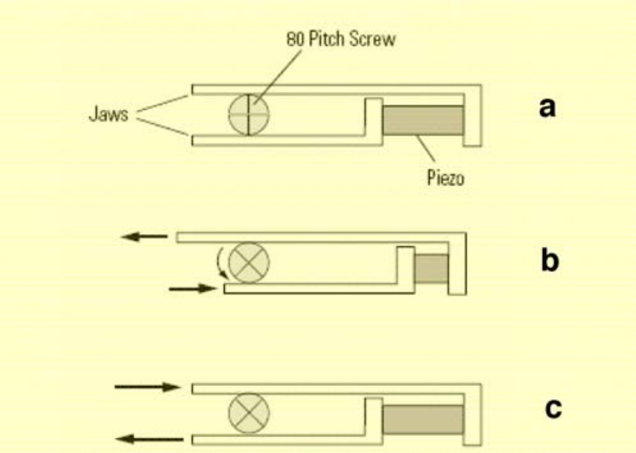

Fig. 3 Schematic of the action of the picomotor (New Focus [45])

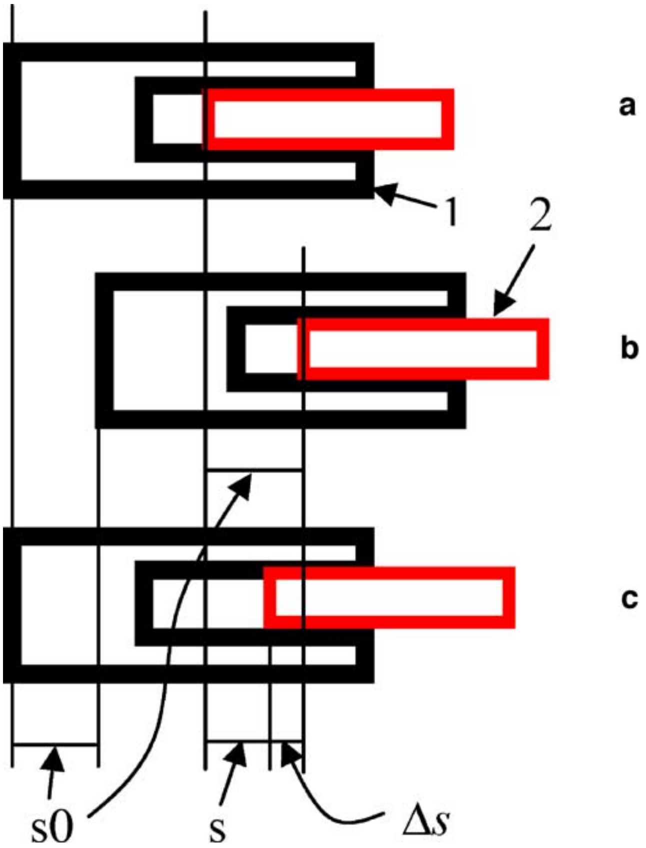

Fig. 4 Friction/inertia principle

The terms "stick-slip" in the stick-slip actuator refers to two phases of generated motion, namely the holding phase and the sliding phase. In particular, a conventional one-degree-of-freedom (translational motion) piezoelectric actuator (piezo-translator for short hereafter) is attached with object 1 illustrated in Fig. 3. Given a voltage wave form to the piezo-translator, object 1 and object 2 perform motion in two phases: the holding phase (two objects hold together due to the friction) and the sliding phase (two objects slide relative to each other due to the inertia); consequently, object 2 performs an accumulated step motion (to the right in the case of Fig. 3). In this configuration, the piezo-translator serves like a driver, while object 2 as an output shaft of the whole actuation system. Generating motion with this manner has several advantages: (1) theoretically unlimited range of displacements, (2) the large displacement range does not compromise the output force, and (3) a displacement resolution in the nanometer scale can be achieved. An implementation of this stick-slip principle in two DOF micro-actuators is reported by Zhang et al. (2006) [59]. However, the stick-slop actuation is limited in speed and payload due to friction as a part of its working principle. Typically, the payload would be dozens of N and speed would be around 0.03 Hz [59].

3 Manipulator systems for micro motion

A single actuator is aimed only at producing a linear motion between the input and output. Furthermore, the motion at the output end is in general small, less than 1 mm except for the stick-slip and inchworm actuators. However, these two kinds of motors have poor payloads and generally sensitive to manufacturing errors and environment disturbances.

Manipulator systems for micro motion are researched in order to realize non-linear controlled motions at the end-effector in addition to (1) high payload, (2) long motion range, and (3) high accuracy. Nevertheless, the macro-micro manipulator is driven by the actuators. In the following we comment on several works on the macro-micro (M-m) manipulators published in the literature [22, 31, 36, 41, 50, 54–57].

Rigid M-m manipulators have been studied by Khatib [36] and Hogan et al. [22]. The flexible M-m system, studied by Yoshikawa et al. [57], Yim and Singh [55], Lew [41], Jiang and Goldenberg [31] and Xu et al. [54], have flexible macro manipulators (M-part), and rigid micro manipulators (m-part) are attached on the tip of the macro part. The flexible manipulator has long arms and can move in a large workspace, but it cannot be controlled precisely at high speed due to the structural deformation of links. The rigid micromanipulator can achieve fast and precise motion.

Yoshikawa et al. [57] have designed controllers for the flexible macro-micro manipulator system. The controller was designed as a PD feedback for joint angle control of the macro part and an inverse control law for the end-point control of the micromanipulator. Xu et al. [54] proposed a PD control + fuzzy logic controller for the macro manipulator and a feedforward control for the micromanipulator. Yoshikawa et al. [57] described a quasi-static hybrid position/force control of flexible manipulators by macro-micro manipulator system. In this macro-micro system, the macro manipulator is controlled to roughly realize the desired position and force by a simple PD feedback, and the micromanipulator compensates the position and force errors caused in the macro part. These control algorithms are verified by experiment.

Hodac and Siegwart [21] pointed out that mounting a fine manipulator on a coarse manipulator would produce a dynamic interaction that might degrade the performance of the whole system. A micromanipulator composed of a flexible suspension and of an electrodynamic actuator placed between the endpoint and ground was proposed and it can reduce the dynamic coupling between the two systems.

Lew [41] discussed the contact control of a flexible macro-micro manipulator. The controller is combined with the force damping controller and the inertial force active damping controller. In his study, using a force sensor at the wrist and a strain measurement at the flexible link, the micromanipulator regulates the contact force to a desired value without causing contact instability.

In Jiang's (1998) [31] research, an ideal manifold is used to prescribe the desired performance of a flexible macro-micro manipulator in terms of end-effector trajectory tracking and link vibration damping. The control scheme is divided into two parts: one is to compensate the nonlinear forces due to the micro arm motion, and join motion of the macro arm directly; the other is to compensate the nonlinear forces due to the link flexural motion of the macro arm in such a way that stability of the system would be maintained.

Vliet and Sharf [53] described the development of a macro-micro manipulator test-bed at the University of Victoria. The facility includes a two-DOF macro-manipulator with two flexible links, to which is attached a three-DOF small robot. The manipulators rest on a planar glass-top table that makes them ideal for studies relevant to space applications. That paper presents the design of the complete system, focusing on the micromanipulator and its integration with the existing hardware, the dynamics model and the frequency domain validation results.

Angeles et al. [2] studied the design of the mechanical structure of an 11-axis robot to accomplish accurate positioning and velocity-controlled tasks in the presence of a flexible substructure. The manipulator is designed as a cascade of three modules, the proximal one being termed the macromanipulator which is responsible for a long reach and a high flexibility. The other two modules, comprising the seven-axis micromanipulator, are responsible for the accurate positioning and orientation of the tool attached to the end-effector.

In our previous work, we proposed a parallel structure for macro-micro systems [56]. The main idea is to incorporate two types of actuators, i.e., DC servomotor for the macro motion and the PZT actuator for the micro motion, into a common framework, as shown in Fig. 5. In this new design, the macro-motion (DC motor) and micro motion (PZT actuator) are connected by following a “parallel” structure in the sense that the macro motion mechanism and micro-motion mechanism are not possibly arranged in a serial structure; instead the two motions are coupled under one compliant mechanism framework to produce the motion at point B. Such a parallel structure eliminates the interface between the macro motion mechanism and the micro-motion mechanism. It is noted that such an interface can be a problematic area for errors. Another sense of parallel structure with the manipulator shown in Fig. 5 is that the platform with point P as an output motion is supported by three same legs.

4 Compliant mechanisms for micro motion

4.1 Compliant mechanism concept

Compliant mechanisms are a relatively new class of mechanisms that utilize compliance of their constituent elements to transmit motion and/or force. A compliant mechanism is a flexible monolithic structure with notches and holes cut on them. A compliant mechanism is a device that moves solely by deformation, typically by utilizing flexures in place of conventional bearings. Since these devices do not entail any sliding or rolling, they are free of backlash and Coulomb friction, and thus have perfectly smooth mechanics. The absence of hard nonlinearities in compliant mechanism behavior places no fundamental physical limitations on the resolution of position or force control. Additionally, the absence of conventional joints or other bearing surfaces produces a clean device that is free of lubricants or other contaminants and thus is extremely conducive to clean environments. Complaint mechanisms can be designed for any desired input/output force/displacement characteristics, including specified volume/weight, stiffness, and natural frequency constraints. As flexure is permitted in these mechanisms, they can be readily integrated with unconventional actuation schemes, including thermal, electrostatic, piezoelectric, and SMA actuators. Fig. 6 (Kota et al., 1999) [38] shows some examples of compliant micromechanisms.

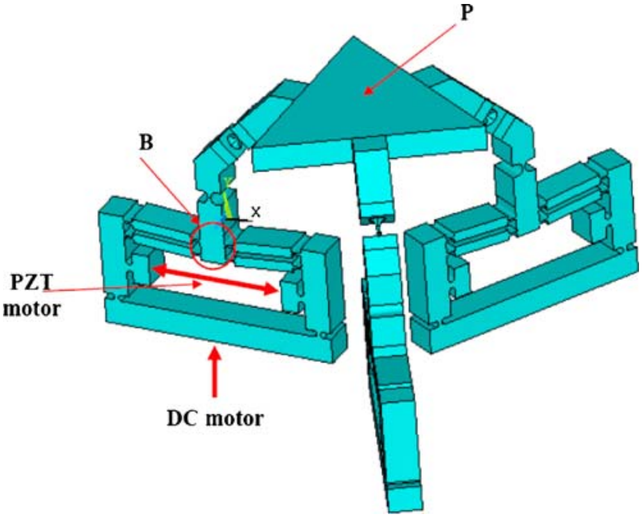

Fig. 5 Three-dimensional model of the spatial HMM

4.2 Compliant mechanism manipulator

A micro-motion system based on the compliant mechanism concept can be constructed as a closed-loop configuration or a parallel manipulator. The closed-loop mechanism configuration can provide better stiffness and accuracy, which should be one of the important design goals for micro-motion systems. Moreover, they allow the actuators to be fixed to the ground, which thus minimizes the inertia of moving parts.

Since the 1970s, compliant micro-positioning stages, which consist of piezoelectric actuators and flexure hinges, and which can produce linear motions have been developed. Scire and Teague [49] designed a compliant single-axis stage that combined a PZT actuator and a flexure pivoted level operating as a displacement amplifier. Furukawa and Mizuno [15] designed a flexure-hinged translation stage, which combined a linkage as a mechanical amplifier and a guidance system for rectilinear movement. It is noted that these types of compliant mechanism were only able to generate linear motions and hence, their applications are limited. Since the 1980s, micro-positioning stages that can produce more complex motions than just linear translations have been developed. Lee and Arjunan [40] designed a spatial 3-DOF compliant micro-positioning in-parallel stage.

The design methodology for compliant mechanisms is developed along with two directions [18, 24–27, 38, 39]. One direction is based on based on the concept called pseudo-rigid-body model (PRBM). The other direction is based on a technique in solid mechanics called topology optimization. By its nature, the PRBM is an equivalent rigid body description of compliant mechanisms. The relationship or mapping between a compliant mechanism and its PRBM has been extensively studied, which has resulted in some useful mapping formulae [3, 6, 19, 24, 29, 46, 61]. Finite element analysis and experiments were performed and their results were compared with the results predicted by the PRBM approach [29, 43], and a good agreement of the results obtained by these approaches was achieved. The optimization of compliant mechanisms can found in literatures [9, 13, 14, 20, 48].

Ryu et al. [47] designed a flexure hinge based XY-theta stage and discussed the optimal design of the stage. In our previous work, a compliant parallel stage was developed [60, 61]; see Fig. 7. In Figure 7a, there are three PZT actuators denoted by PZT 1, PZT 2, and PZT 3, respectively. These actuators drive the compliant material to make it

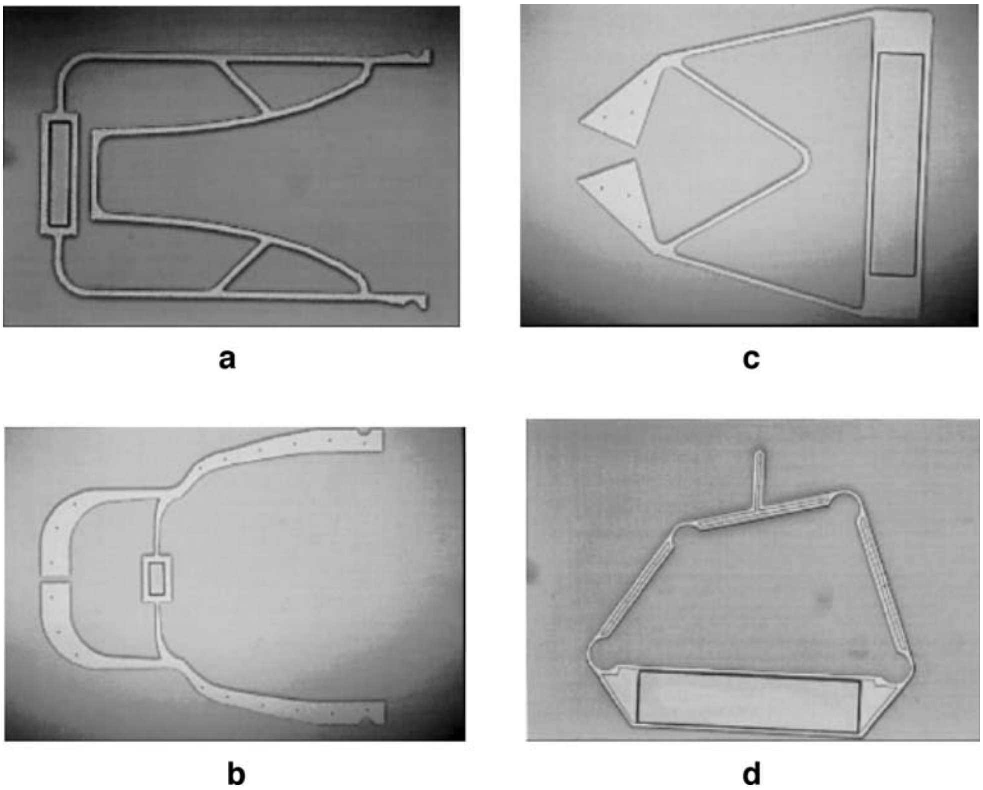

Fig. 6 Some examples of micro compliant mechanisms (Kota et al. [38]) Crimping mechanism. (b),(c) Compliant grippers. (d) Micro four-bar mechanism

change its deformation. Its deformation is further introduced by three points A, B, and C (see Fig. 7a). There will be a plate assembled with these three points such that the motions of A, B, and C are converted into the motion of the plate. Finally an end-effector will be attached on this plate. Figure 7b shows the system which is assembled in which the needle is the motion of the end-effector. Some other compliant manipulators can be found in [25, 27, 30, 51].

4.3 Compliant micro grippers

Grasping and manipulating small or micro-objects is required for a wide range of applications, such as the assembly of small parts to obtain micro or miniature systems, surgery and research in biology and biotechnology. The most evident difference between the micro and the macro worlds is the increasing importance of adhesion (or surface) forces, which become stronger than inertial (or mass) forces as size decreases, thus rendering, for example, releasing objects more difficult than grasping them. Additional problems for a micro grippers drive from the need for achieving dexterity, high accuracy and high speed in a very small workspace, and from the need for operating in different working environments, such as air, liquids or clean room.

An effective mechanical micro gripper should possess three main characteristics: (1) the ability to grasp steadily objects with different shape; (2) high positioning accuracy; and (3) a large number of degrees of freedom. These characteristics can be well satisfied by the compliant mechanism concept.

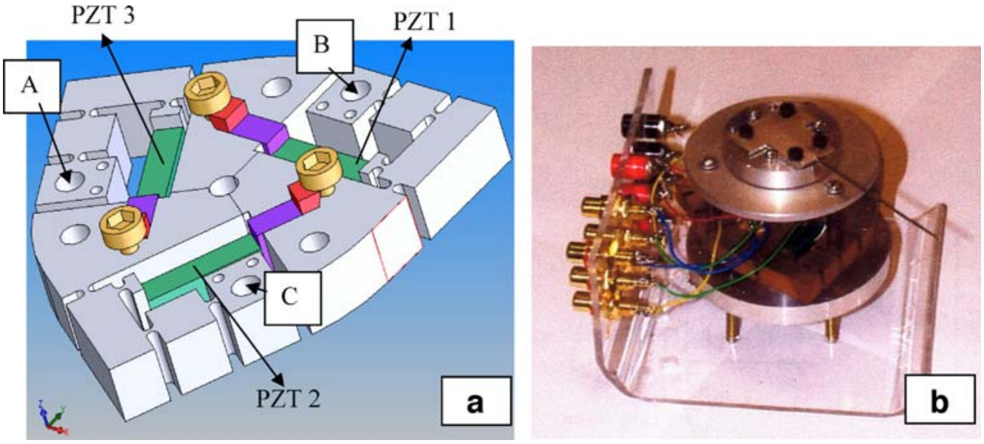

Fig. 7 Schematic diagram of a compliant mechanism (a: The RRR mechanism; b: The RRR mechanism assembled with the three PZT actuators) (Zhang et al. [58])

Several micro grippers have been developed using different kinds of actuating methods [4, 8, 10, 28, 35, 37, 44]. Kim et al. [37] demonstrated a surface-micromachined polysilicon microgripper that is electrostatically driven by interdigitated comb electrodes. Suzuki [52] developed a microfabricated flexible microgripper that is electrothermally and electromagnetically driven. Ikuta et al. [28] developed micro-active forceps with microgripper and built-in optical fibre scope for eye microsurgery on the retina. Keller and Howe [35] described high aspect ratio moulded polysilicon tweezers with integrated in situ phosphorous doped thermal expansion actuator beams and piezoresistive polysilicon strain gauges for tactile feedback. Nogimori et al. [23] introduced a microgripper actuated by laser power. Du et al. [8] presented the development of a thermally driven microgripper for micro-assembly and micro-operation applications. Two design configurations for a silicon-based microgripper with integrated thermal expansion actuator and microsensor were proposed and studied in this work. The opening distance of the microgripper is up to 120 μm.

Carrozza et al. [4] described the design, fabrication and performance of a few prototypes of LIGA micro-gripper. LIGA represents lithographie, galvanoformung, and abformung in German. The mechanical configuration of a LIGA micro-gripper is illustrated in Fig. 8 (Note that all presented dimensions are in millimeters).

The working principle of the micro-gripper is as follow: when the piezoelectric actuator is driven by a suitable voltage it elongates, the two pairs of parallel thin beam visible in the left side of the gripper act as flexure hinges; the final effect is a total translation of each gripper arm which makes the two fingers approach. The manipulator can operate objects between 38 μm and 100 μm. But the control of the piezoelectric actuators is open loop.

A similar flexure-based structure of force-reflective microgripper (see Fig. 9 [11, 12, 16]) was built in CIM Lab at Vanderbilt University [16, 17]. The gripper shown in Fig. 9 is actuated by piezoelectric ceramic. Force and displacement information is provided by strain gages.

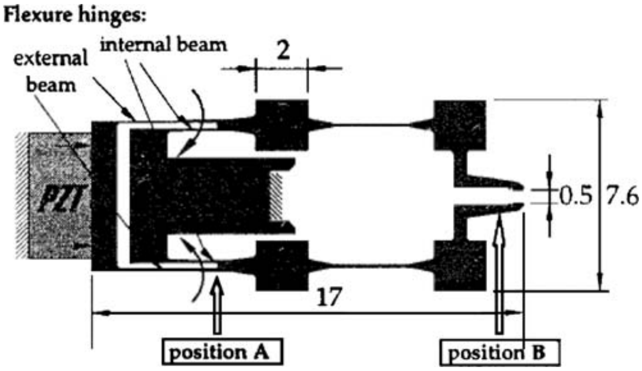

Fig. 8 LIGA micro-gripper (the units in the figure: mm) [4]

Chonan et al. [5] studied the hybrid position/force control of a two-fingered miniature gripper. The fingers are flexible cantilevers actuated by piezoelectric bimorph strips at the base and are supported by linear ball bushings which ride on a steel shaft. The cantilever is driven by the bending deformation of the ceramic actuator. The maximum displacement of the actuator is approximately 300 μm and the resolution is 5 μm. In their research, they use a linear slide mechanism to realize the coarse motion. The PID control algorithm is introduced to drive the gripper.

Kallio et al. [33] designed a three-DOF piezohydraulic micromanipulator (see Fig. 10). The actuation system consists of a piezoelectric actuator, a small tank and a bellows. The bellows is a spring type of passive component, i.e., force required to deform the bellows is directly proportional to the displacement. It can get a displacement about ± 250 μm. The manipulator consists of three identical piezohydraulic actuation systems. They are connected by a mobile platform forming a parallel tripod-like configuration. It is reported that the planar workspace of the manipulator is 1.5 mm and 0.6 mm and its maximum vertical displacement along z axis is about 0.25 mm, and the displacement resolution of the manipulator is better than 1 μm. The following figure is an overview and photograph of the manipulator.

The main applications of the micromanipulator presented in here are in the area of biotechnology, where needs for automatic operations will further increase in the future [32, 34].

5 Micro-motion systems in industries

We classify micro-motion devices based on the following aspects:

- The motion type. Motion can be classified into two groups: one is applicable to simple linear motions, and the other is to complex non-linear motions.

Fig. 9 Microgripper at Vanderbilt University (Goldfarb and Celanovic [16])

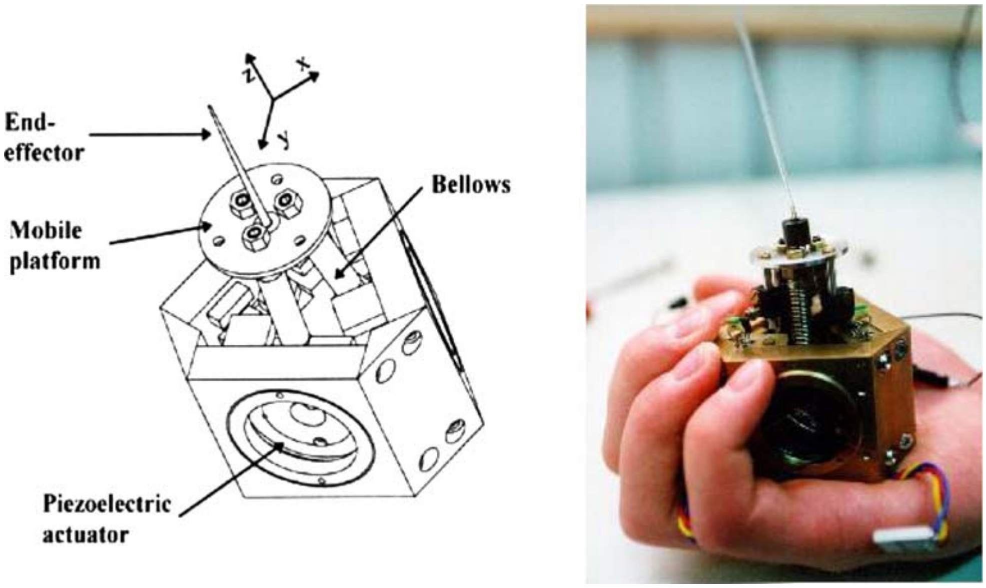

Fig. 10 Photograph of a 3 DOF piezohydraulic micromanipulator (Kallio et al. [33])

- The motion range/accuracy. Motion ranges are classified into (i) 1 ~ 100 μm, (2)100 ~ 1000 μm, and (3) greater than 1000 μm.
- The mechanism structure. Two groups are classified: one using compliant materials, and the other using rigid body materials.
- The loop configuration. Two groups are classified: one with the open-chain structure, and the other with the closed-chain structure.
- The actuation mechanism. Two groups are classified: one with PZT actuators and one with non-PZT actuators.

Table 1 lists the state of arts of industrial developments in micro-motion systems found in the current market. Several remarks are given as follows:

Remark 1 Burleigh's Freedom ™ 1500 automated nanorobot system offers the automated five-axis alignment, with 20-nm linear (X, Y, and Z axis) and arc-sec rotational resolution all revolving around a true virtual point ($^{\theta}$x and $^{\theta}$z) in space.

Remark 2 Burleigh's Freedom *TSE 150* positioning system combines Inchworm Motor, precision translation stage, and an integral linear encoder. *TSE 150* is capable to achieve maximum range of 25 mm in translation stage (X, Y, and Z axis), while the motor resolution is smaller than 20 arc-sec over 25 mm for rotations around X axis and Z axis ($^{\theta}$x and $^{\theta}$z respectively).

Remark 3 The New Focus Inc. [75] employs a picomotor actuator (a piezoelectric actuator that turns a screw-allows mounts, stages, and micro-meter-replacement actuators to achieve < 0.1 μm resolution) to each stage such that this system is capable to achieve combinations of translation stages (X, Y and Z axis) and rotation stages ($^{\theta}$x, $^{\theta}$y and $^{\theta}$z axis).

Remark 4 *Luminos Industries Ltd.* supplies photonics positioner (I 3000 - XYZ three axes stage) with the cost of CAD 3,500. Their system uses a stepper motor, with a travel range for X, Y, and Z axis of 0.5 mm, 0.5 mm, and 12.7 mm, respectively. Applicable Electronics, Inc. has the computerized motion control (CMC-4) that is capable of achieving a larger travel range (up to 50 mm for three axes: X, Y and Z) with the resolution up to 0.003 μm. The CMC-4 is designed for use in the scanning microelectrode system applications and is also equipped with National Instruments PCI-7334 motion control card, software drivers, and motion control interface unit (MCI-1). The system's cost is around US$10,000. Siskiyou Inc. [70] provides a micro injection manipulator (MX7630) that is capable of achieving motion in three axes: X, Y and Z motions. The travel range of this system is 20 mm, for each axis. Each axis is motorized by a closed-loop DC servo motor that could carry the maximum load of 5 lbs. MX7630 has resolution of 1 μm. The cost for the MX7630 system with controller is around US$ 4,000. *Newport Corporation* supplies CMA-25 CCCL system that is basically a unit of linear actuator system that is powered by either stepper motor or DC servo motor (based on the customer's order). The single unit of CMA-25 CCCL is capable to

Table 1 Manipulators found in the current market

Company	Model	Motion type	Motion range	Resolution	DOF motion	Actuation mechanism
Physik Instrumente [63]	M505	Linear motions	> 1000 µm (15000–300000 µm)	< 100 nm	X-Y-Z axes	DC and dtepper motors
Applicable Electronics [62]	CMC-4	Linear motions	> 1000 µm (30000–50000 µm)	49 nm	X-Y-Z axes	Stepper motors
Eppendorf [64]	5171	Linear motions	> 1000 µm (25000 µm)	160 nm	X-Y-Z axes	Stepper motors
Piezo Systems [65]	Piezo 2-axis	Linear motions	100–1000 µm (400 µm)	25 nm	X-Y axis	PZT actuators
Burleigh Instruments[1] [66]	Freedom 1500	Complex non-linear motions	> 1000 µm (25000 µm)	20 nm	X-Y-Z- $^{\theta}$x-$^{\theta}$z axes	Inchworm motor
Burleigh Instruments[2]	TSE-150	Complex non-linear motions	> 1000 µm (25000 µm)	20 nm	X-Y-Z- $^{\theta}$x-$^{\theta}$z axis	Inchworm motor
Kyocera [67]	X-Y stages	Linear motions	User-selectable	1 nm	X-Y axis	Ultrasonic motor
Olympus India [68]	ONU-31P	Linear motions	> 1000 µm (25000 µm)	0.1 µm	X-Y-Z axes	Ultrasonic motor
Sutter Instrument [69]	MP-285	Linear motions	> 1000 µm (25000 µm)	40 nm	X-Y-Z axes	Stepper motor
Siskiyou [70]	MX7600	Linear motions	> 1000 µm (20000 µm)	0.005 µm	X-Y-Z axes	AC motor
Micro Pulse Systems [71]	L-114	Linear motions	> 1000 µm (13000 µm)	0.1 µm	X-Y and X-Y-Z axes	Stepper motor
Baldor [72]	LSC	Linear motions	User-selectable	25 nm	X-Y axes	AC/DC motor
University of California [73]	Electromagnetic micro-manipulator	Linear motions	1–100 µm (40 µm)	Sub nanometer	X-Y axes	Micro-coils and magnetic micro-tips
Piezosystem Jena GmbH	PXY 400	Linear motions	100–1000 µm (400 µm)	Sub nanometer	X-Y axes	PZT actuators
Physik Instrumente	P-730 P-731	Linear motions	1–100 µm (80 µm)	< 1 nm	X-Y axes	PZT actuators
The New Focus Inc[3]	Motorized kinematic stage	Complex non-linear motions	100–1000 µm (300 µm)	< 30 nm	X,Y,Z, $^{\theta}$x, $^{\theta}$y $^{\theta}$z axes	Picomotor
PIEZOMAX Technologies, Inc. [76]	N-XY200 Series Nanopositioners	Linear motions	100–1000 µm (200 µm)	1 nm	X-Y axes	PZT actuators

achieve one type of degree of freedom motion Thus, to achieve three axes degrees of freedom motions, three units of CMA-25 CCCL are required. Each unit of CMA-25 CCCL has a travel range of 25 mm with the resolution of 0.05 µm. Three units of of CMA-25 CCCL, controller, and driver would cost around US$ 10,000.

Remark 5 *Piezosystem Jena, Inc.* [74] provides the actuators series R/RA that consist of piezoelectric actuators, integrated strain gage measurement system and EVD 50 amplifier module. Series R/RA is capable to achieve motion of 25 µm with sub-nanometer resolution. Series R/RA system would cost around US$ 5,000. *Mad City Labs Inc.* supplies actuator model PZT 3 that is capable to achieve the displacement of 18 µm. Single unit of PZT actuator is offered with the cost of US$ 135, while its controller (need to be purchased separately from different manufacturer such as Apex Microtechnology Corporation) is offered with the cost of US$ 1,000. *Physik Instrumente* (PI) Gmbh & Co [63] *sells the preloaded closed-loop piezoactuator with the cost of US$ 1,273, while the cost of LVPZT Piezo Amplifier/Position is US$ 4,374. TOKIN NEC America Inc.* offers AE0505D16 Piezoelectric Multilayer Actuator with the cost of US$ 151.78 per unit, while the cost for its controller is US$ 1500.

6 Summary of technology limitation and economic implication

This section presents a summary of technology limitation and economic implication of various actuators and micromanipulators. This summary covers the following systems:

(1) Direct current (DC) motor
(2) Stepper motor

(3) Piezoelectric (PZT) actuator
(4) shape memory alloy (SMA) actuators
(5) Inchworm actuator
(6) Ultrasonic motor
(7) Picomotor actuator
(8) Stick slip actuator
(9) Manipulator systems for micro motion
(10) Compliant mechanisms for micro motion
(11) Electromagnetic-based manipulator for micro motion

6.1 Direct current (DC) motor

DC motor is bulky and generates significant amount of unwanted heat and possesses some rigid joint problems (e.g., backlash and friction). The bulky size of the DC motor hinders the use of this kind of motor for micro-motion applications. The unwanted heat, backlash and friction also limit its accuracy. Typical speed for DC motor is from 12000 to 20000 revolutions per minute (RPM). The price of DC motors vary from approximately US$ 5 ~ US$ 100.

6.2 Stepper motor

Stepper motor is incapable of providing smooth continuous motion and generates significant amount of unwanted heat and bulky. Like the DC motor, the bulky size of the stepper motor makes it less attractive for micro-motion applications. Typical speed for stepper motor varies from 48 to 400 steps per revolution. Depending on the individual performance, the price of the stepper motor is inexpensive, varying from approximately US$ 19 ~ US$ 100.

6.3 Piezoelectric (PZT) actuator

PZT actuator has limitations such as highly nonlinear input and output behavior, creep and hysteresis. Because of those limitations, the use of the PZT actuator has to be accompanied with a closed-loop controller. The PZT actuator requires relatively high voltage and has relatively small motion range. The response of the PZT actuator is very high (sub-milisecond) and the maximum speed can be achieved is from a few hundred microns/second to a few millimeters/second. The price of the PZT actuator is inexpensive, which varies from approximately US$ 100 ~ 160 per unit.

6.4 Shape memory alloy (SMA) actuators

The SMA has poor fatigue properties; this means that while under the same loading conditions (i.e., twisting, bending, compressing), a steel component may survive for more than one hundred times more cycles than an SMA element. Thus, the SMA actuators possess limited cycle time. In addition, the SMA actuator also has limited strain, inherent non-linearity and hysteresis. The SMA actuator is still relatively more difficult to manufacture compared with other materials such as steel and aluminum. The response time of the SMA actuator is approximately 4.6 ~ 6.5 ms, whereas its speed varies from 90°/second to 180°/second. The cost of the material is high, approximately US$0.30–US$1.50 per gram for wire forms.

6.5 Inchworm actuator

Although theoretically, the inchworm motor has unlimited motion range, the force generated by inchworm motor is small. The force produced by inchworm motor varies from 0.3433 to 45 N. Some researchers report the modified inchworm actuator is capable of achieving force levels at 90 N, but this typically requires a trade-off between backlash and friction and stick-slip at the cost of significantly reducing travel speed. The inchworm actuator is capable of achieving speed between 2 μm/second and 5 μm/second. The price for the inchworm motor is relatively expensive, which varies from US$ 3500 (Model RS-800 from Burleigh’s Freedom ™) to US$ 12900 (Model TS-100/RS-800 from Burleigh’s Freedom ™).

6.6 Ultrasonic motor

The performance of the ultrasonic motor is limited by the energy dissipation due to friction. The energy dissipation reduces motor efficiency. The sliding of the rotor due to its inertia does not enable an instantaneous start-and-stop operation. Hence, it is difficult to achieve a precise control over the displacement of the rotor. The typical speed for the ultrasonic linear motor is approximately 600 mm/s, while the speed for the ultrasonic rotary motor is around 5100 rpm. The price for the ultrasonic motor varies from US$ 75 to US$ 750.

6.7 Picomotor actuator

The picomotor actuator produces small variations in screw rotation from step to step can lead to repeatability errors. These errors are accentuated if the force acting against the picomotor’s motion changes throughout its travel, as when moving against a spring. The picomotor actuator is capable of achieving the speed of 1.2 mm/min or 3 ~ 4 rpm for the rotary kind. The price of the picomotor actuator is around US$ 895.

6.8 Stick-slip actuator

The drawbacks of stick-slip actuator are an inherent backlash, a micro vibration after each slip phase (the oscillation occurred due to the friction between the slider and the actuator during the slip phase) and low driving force. The wear problems in the sliding contacts due to the high local contact resources are a potential source of failure after a certain service time. Some of the stick-slip motors can be found with the speed, varying from 500 mm/s to 600 mm/s. It is noted that the company called Physik instrumente offers stick-slip actuators, namely P-661, M-663, and M-662. The price of stick slip actuator in the market varies from US$ 700 to US$ 4000.

6.9 Manipulator systems for micro motion

In Sects. 4 and 5, manipulator systems for micro motion were discussed. These mechanisms may be driven by DC/stepper motors, PZT actuators, and so. Therefore, the technology limitation of these mechanisms can inherit from those actuators. As far as the mechanical part (or the part excluding the actuator or motor) is concerned, the manipulator system suffers from problems such as clearance and friction due to the interfacing between two components which further cause the backlash problem. Due to these technical limitations, the cost of manufacturing the manipulator system for micro motion is relatively expensive with respect to a particular accuracy level it is expected to achieve; see the discussion in Sect. 5 for more details.

6.10 Compliant mechanisms for micro motion

The compliant mechanism entails some disadvantages. The flexure hinges of the compliant mechanism entail a limited range of motion in the desired axis of rotation, whereas the conventional revolute joints have an infinite range of motion in the rotational axis. Furthermore, the flexure hinges are not fully fixed in all directions of loading except at the rotational axis. Thus, the flexure hinges will twist when subjected to torsional loads and exhibit shear deformation when subjected to shear loads. Because the operation of compliant mechanism relies on the deformation of the material, especially repeated deformations, the compliant mechanism could also easily induce the fatigue problem. The price of making a compliant mechanism for the system shown in Fig. 6 would be around US$ 750. If the material is plastic, the use of laser cutting may reduce the manufacturing cost to US$ 100 – 200.

6.11 Electromagnetic-based manipulators for micro motion

This kind of motor integrates micro-coils and magnetic micro-tips for localized positioning of micron sized magnetic objects in fluids. For cell applications, most of these techniques rely on the micro-manipulation of a magnetic particle positioned inside a cell wall or bound on the surface of a cell. Further, with the dimensions of such a device becoming smaller, magnetic field intensity is restricted by temperature rise caused by heat generated inside the coil windings. In addition, because of leakage flux of magnetic materials, the power per unit volume of such a device is further reduced. The heat generated in the coils becomes comparable to its input power. This further leads to very low efficiency in terms of power. The electromagnetic motor can achieve maximum speed of approximately 10000 rpm. The cost for such a device is higher than that for compliant mechanisms.

7 Conclusion

There are four types of micro motions in terms of motion ranges: (a) < 1 μm, (b) 1 ~ 100 μm, (c) 100 ~ 1000 μm, and (d) > 1000 μm. The most challenging appears to be on type (1) and type (2). In micro-motion applications demanding motion accuracy of 1 – 100 μm, i.e., type (2), the DC and stepper motors are recommended, especially for applications demanding a large motion range (> 1 mm). However, when applications (chip assembly) require high acceleration (e.g., 5 g), the DC and stepper motors may not be proper because of heat generated. In such applications, the PZT actuation system may be a solution to go, because its natural advantage to produce a high speed motion and high payload. It is also noted that when high acceleration is demanded, often high payload may also be desired. In this case, the PZT actuator is definitely the best choice.

To achieve a motion that demands high accuracy (< 1 μm) i.e., type (1), high payload (~100 N), and large motion range (~1 mm), the PZT actuator is the best choice. The problem of non-linearly and hysteresis with the PZT actuator can be solved with modeling and feedback control. The current sensor technology can readily allow the measurement of displacement in the resolution of 0.01 μm (strain gauge); therefore, the sensing system will not likely compromise the excellent performances of the PZT actuator.

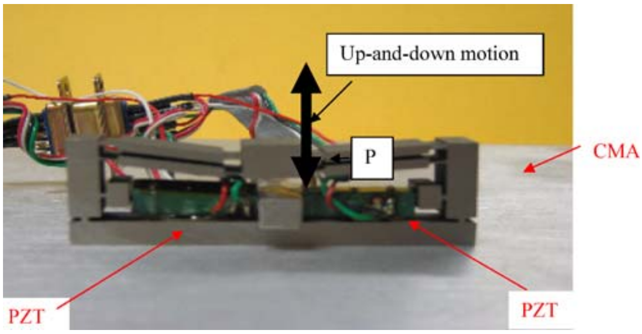

Fig. 11 Experiment setup of the CMA

One of the problems with the PZT actuator is perhaps its yet too small motion range. The stacking of piezo slices is one popular solution. However, the length of a piezo stack is limited by two factors: (1) stress induced in the slice and (2) error created at the end of the stack. The current stacking technology only allows for the length of the piezo stack up to 10–20 mm with the 100 slices, each of which has a thickness of about 100 μm. Due to the technology limit in the stacking, the motion range of a single PZT actuator is currently about 20 μm with the absolute accuracy at the end of the stack being about 0.01 μm.

It is noted that from a point of view of cost, the PZT actuator is relatively cheaper than the DC and stepper motors if the absolute accuracy, speed, and payload are considered. This implies that to achieve the same performance with exception of motion range, the PZT actuator has provided a cost-effective solution.

The future research direction is suggested to be on a cost-effective PZT technology for large motion ranges without a compromise of its advantages. The technology may need to take away from the stacking technology, but to take the amplification technology based on the compliant mechanism concept. This is because the compliant mechanism generates motion based on the material deformation which is, theoretically, of unlimited small resolution. The second reason is that the number of interfaces with the stacking technology (e.g., 100 layers implying 100 interfaces) will be far larger than that with the compliant mechanism (e.g., perhaps only one or two). Due to the fewer number of interfaces with the design concept of an integrated PZT and compliant mechanism amplifier, the absolute accuracy of such a system will very likely be higher than that of the stack PZT actuator at present.

Figure 11 shows a compliant mechanism amplifier developed at our research laboratory [56]. This amplifier is based on a five-bar topology and has shown its superior performance (the amplification ratio and system natural frequency) over the other systems. The system is driven by two PZT actuators which further drive a symmetrical five-bar mechanism. The end motion is the vertical movement at point A (see Fig. 11) which is amplified. The manufacturing cost of this system is very cheap with laser cutting or water jet processes. One of the problems with the compliant mechanism is its repeated deformation which demands attention to its reliability due to premature fatigue. Thus, the future research direction should be directed to the finding of a technique that can predict a fatigue problem in the compliant mechanism. Such a technique is to facilitate the development of a more reliable compliant mechanism, in which the life of the use pattern of the compliant mechanism can accurately be predicted and accordingly optimized.

Another research direction is the development of an integrated technology which puts together the PZT actuator, compliant mechanism, and DC motor stepper to realize micro motions that demand high accuracy and large motion range (> millimeters compatible to the motion range of stick-slip actuator or inchworm actuator). The rationale behind this technology is that the DC motor is used to share a large motion range while the PZT actuator and compliant mechanism are responsible high accuracy with the compliant mechanism is further used to serve as a frame to bring the DC motor and PZT actuator together.

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