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Overview of flexure-based compliant microgrippers

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Abstract. Microgripper is an essential device in the micro-operation system. It can convert other types of energy into mechanical energy and produce clamp movement with required chucking force, which enables it a broad application prospect in the domain of tiny components' processing and assembly, biomedicine and optics, etc. The performance of a microgripper is dependent on its power supply, type of drive, mechanism structure, sensing components, and controller. This paper presents a state-of-the-art survey of recent development on flexure-based microgrippers. According to the drive type, the existing microgrippers can be mainly classified as electrostatic microgripper, electrothermal microgripper, electromagnetic microgripper, piezoelectric microgripper, and shape memory alloy microgripper. Additionally, some different mechanisms, sensors, and control methods that are used in microgripper system are reviewed. The key issue of how to choose those components in microgripper system design is also addressed.

Keywords: microgripper; actuator; sensor; mechanism; control

1. Introduction

Microgripper is a micro device used for manipulation of micro-objects in microassembly and microsurgery. It is one of the key elements in micro-robotics and micro-assembly technologies for handling and manipulating micro-objects without damage. For instance, microgripper can be used for pick-and-place operation of microparticles in material sciences. In addition, micropipettes, optical tweezers and magnetic tweezers are used by most of the biologists for such applications as stem cell sorting, gene and molecular delivery, cellular diagnostic, and single cell manipulation (Ali *et al*. 2011).

In micromanipulation and microassembly systems, microgrippers act as end-effectors which contact with the manipulated objects directly. They are usually less than 100 μm in dimension and fragile (Lu *et al*. 2006, Bassan *et al*. 2009, Kim *et al.* 2008). Therefore, microgrippers play a vital role in micromanipulation and microassembly tasks. A typical microgripper consists of actuator, guiding mechanism, sensor and control components (Kim *et al.* 2008). 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

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most obvious 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 the size decreases, thus rendering, for example, releasing objects are more difficult than grasping them. Additional problems for micro grippers come from the need for achieving dexterity, high accuracy and high speed in a very small workspace, and the need for operating in different working environments, such as air, liquids, or vacuum sites.

Compliant mechanisms are a class of mechanisms that utilize the compliance of their constituent elements to generate motion and force. A compliant mechanism is typically a flexible monolithic structure with notches and holes cut on them. It is a device that moves solely by deformation, i.e., by using flexures instead of conventional mechanical bearings. These devices are free of backlash and Coulomb friction since they do not possess any sliding or rolling components, so they have perfectly smooth mechanics. The absence of hard nonlinearities in compliant mechanism behavior places no fundamental physical limits on the resolution of position or force control. In addition, the lack of conventional joints or other bearing surfaces produces a clean device that is free of lubricants or other contaminants, and thus, it is extremely conducive to clean environments.

In the last decade, the developments on material and actuation of flexure-based compliant microgrippers are accompanied by novel designs and gripping techniques. Microgrippers operate by applying forces which are provided by their actuators. Based on the application, the actuators can be employed as the type of electrostatic, electrothermal, electromagnetic, piezoelectric, and shape memory alloy (SMA). In general, those actuators can be classified in two categories: those working with fields and those changing their shapes (Ouyang *et al.* 2008). The first category uses the forces created by the fields such as electrostatic, electrothermal, and electromagnetic types. The second category of actuators generates, primarily, a strain in the material, which can be converted into a force. Piezoelectric (PZT) and shape memory alloy (SMA) fall into this category.

The rest of the paper is organized as follows. The aforementioned actuators are described in Section 2. In order to complete the properties of microgrippers, the development of mechanical structure is essential. Section 3 reviews the compliant mechanisms for microgrippers. Afterwards, different sensors are elaborated in Section 4, and a review of control techniques is presented in Section 5. Finally, some concluding remarks are generalized in Section 6.

2. Actuators

For a microgripper, the essential component is the actuator that provides the required applied force so as to make the device operate as a gripper. A variety of prototypes of microgrippers with different actuation methods have been developed.

Generally, there are two categories of actuators that can be identified: those working with fields and those changing their shapes (Ouyang *et al.* 2008). The first category uses forces set up by fields such as electrostatic, electrothermal, and electromagnetic fields. Conventional motors such as DC servo motor, AC servo motor, and stepper motor belong to this category. Among them, the electrostatic force is the most attractive for applications in a micro-motion owing to its scaling behavior and material requirements. Only an electrical conducting material is necessary for the electrostatic actuators. The second category of actuators generates a strain in the material, which can be converted into a force. The PZT and SMA fall into this category. In fact, the characteristics of actuators rest with the material properties that also imply the use of special materials. The working principles typical actuators are reviewed as follows.

2.1 Electrostatic actuator

Electrostatic actuators provide the highest frequency response and the lowest power consumption, and they work stably at room temperature. However, the need for relatively large voltages is their major drawback, which is incompatible with typical CMOS electronic drivers.

Traditional electrostatic microgrippers are based on the topology of the comb-drive actuator (Tang *et al*. 1990). Comb drives have been chosen because they are easy to fabricate. They can be made of silicon or metal, which are the device materials as employed in most of the commercial processes. In addition, no movements are involved when the device is in steady state. The comb-drive consists of an array of interdigitated capacitor fingers, in which one set is fixed the substrate and the other one is movable as suspended with springs. In a typical comb-drive, the capacitance is linear with displacement and the driving force is presumptive independent of the position of the moving fingers. While comb-drives are excellent for sensing applications like accelerometers, resonators, and gyroscopes, their applications as microgrippers exhibit some limitations. For instance, the comb-drive configuration demands the use of considerable area and requires some sort of mechanical transmission to couple the tweezers themselves. Fig. 1 shows an example of the implementation of a comb-drive based microgripper (Varona *et al*. 2009).

Another example is shown in Fig. 2. When a voltage is applied to the actuator, one terminal is attached to the stator combs while the other terminal is connected to the rotor combs as shown in

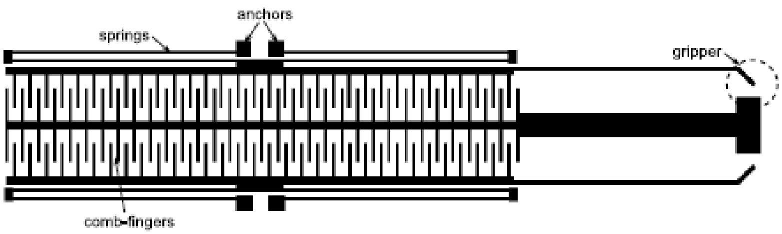

Fig. 1 Typical comb-drive based microgripper actuator (Varona *et al*. 2009)

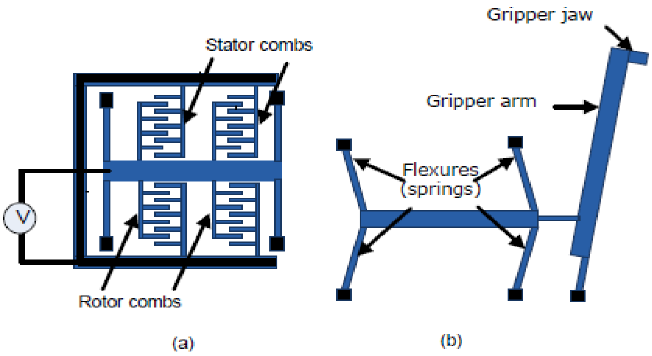

Fig. 2 (a) Voltage applied to actuator combs (b) Gripper arm bent due to force applied by the comb drives (Amjad *et al.* 2008)

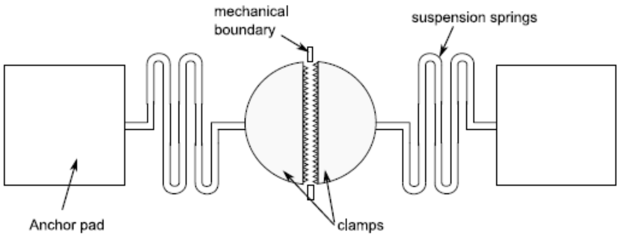

Fig. 3 A microgripper based on parallel-plate capacitance (Varona *et al*. 2009)

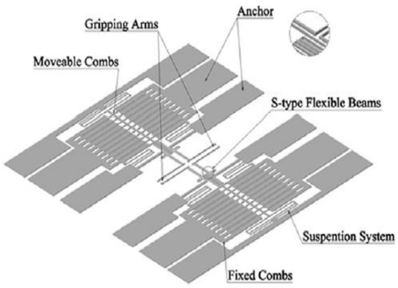

Fig. 4 An electrostatic microgripper design (Hamedi *et al*. 2012)

Fig. 2(a). Attraction force is produced between the comb fingers. Hence, the middle beam, which is hold by four springs, moves towards right, thereby pushing the left arm of the gripper as shown in Fig. 2(b) and gripping the object is placed between the gripper jaws (Amjad *et al.* 2008).

Fig. 3 shows a microgripper based on parallel-plate capacitance. This microgripper consists of two released polysilicon structures separated by a thin gap resembling the construction of a parallel plate capacitor. The two structures are supported by serpentine springs attached to an anchor pad in their far end. When a voltage difference is applied between the two structures, they will tend to collapse against each other due to electrostatic attraction thereby closing the gap. In this way, objects will be gripped by the clamping structures. The face of this structure ensures that the grabbed object is secured and will not slip.

As depicted in Fig. 4, an electrostatic microgripping system using comb drive mechanism was designed, fabricated, and characterized by Hamedi *et al*. (2012). The two independent actuation sets not only provide simultaneous gripping of two microparts, but also introduce the possibility of asymmetrical gripping of micron objects by accepting different amount of actuation voltage. Furthermore, to increase the displacement range, S-type springs are embedded in the structure. Thus, this design owns the advantages of increased displacement range, simultaneous gripping, and asymmetric gripping of microparts, which increase its efficiency.

2.2 Electrothermal actuator

Electrothermal actuators operate with low voltages and offer large output force. Yet, its use in applicable microgrippers is limited due to the high power consumption and high operating temperatures, which are unsuitable for biological and microrobotics uses (Varona *et al*. 2009).

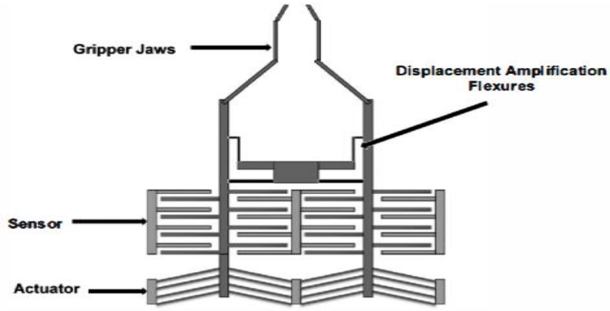

Fig. 5 Schematic diagram of electrothermal microgripper (Ali *et al*. 2011)

Fig. 5 shows an electrothermal microgripper which contains a pair of gripping jaws driven by a pair of electrothermal actuators and an integrated sensor. The flexure used by the electrothermal actuator is bent beam. The applied voltage across the ends of bent beams establishes a current flow through the beams which in turn heats up the beams because of the resistive heating. The increase in temperature causes thermal expansion of the beams that leads to the central beam to move. A small angle is assigned for the beams to attain motion of the central beam in desired upward direction. With the help of horizontal and vertical flexures, the vertical motion of the central beam is transmitted to the horizontal motion of the jaw tip (Ali *et al*. 2011).

Generally, the driving mechanism in thermal actuation is either the bimorph effect or the use of hot-cold arms. In the latter approach, in-plane motion can be produced by microstructures with single-layer material because of the difference in thermal expansion of a narrow hot arm and a wide cold arm. MEMS-based thermal actuators for nanopositioning applications have recently drawn renewed research interest not only because they produce large deflection and force but also due to their fabrication process is compatible with the standard CMOS process.

Without regard to the actuation of the physical affection, thermal actuators are in principle sensitive to the ambient operating temperature. Consequently, their use in nanopositioning applications may be limited (Devasia *et al*. 2007).

Undesired vibrations are partially caused by random motions of particles within materials known as thermal fluctuations which lead to thermal noise. Thermal noise is predominant in micrometric structures such as Atomic Force Microscopy (AFM) cantilevers which characterize high resonance frequencies (in the order of tens of kHz). There must be no vibrations due to position control at manipulator stop positions. This objective depends on the stiffness of the mechanical system, the sensor resolution, and the control algorithm. So these components must be carefully designed (Boundaoud *et al*. 2011).

2.3 Electromagnetic actuator

Electromagnetic gripper uses the electromagnetic force as a driving source to drive the ramp carves and then propels the jaws to achieve the clamping action. It can gain a wide range of opening amount. Furthermore, it has several merits, such as fast response to gripping action, no wearing, simple control, high precision, and large load-carrying capacity.

This type of actuation generates a force via the flow of current by means of a wire coil in the presence of a magnetic field. This concept is extensively used due to its high force and efficiency in comparison with conventional macroscopic actuators. Conventional fabrication methods using wire wound coils can be used to build efficient miniature electromagnetic motors and actuators, even for devices as small as 1 mm (Albrecht *et al*. 2004).

Electromagnetic force is widely used in driving gap, which is closed to actuator with double cantilevers since their structures are simple when they could generate relatively strong force. However, due to pull-in instability, the mobility region is strictly limited (Horenstein *et al.* 1997). Pull-in instability appears and results in an unstable equilibrium gap when a linear force (like the mechanical restoring force) balances with a nonlinear force (like electromagnetic force). As the gap decreasing, the nonlinear electric force grows rapidly that is less than some critical gap. It overwhelms linear restoring force and the gap is suddenly closed up. To enlarge the mobility range, various researches have been carried out in the literature (Nonaka and Baillieul 2001). Some researchers have applied the open loop oscillatory control to a prototype electromagnetic actuator called two wire systems, which is composed of two parallel conducting wires working based on Lorentz force and restoring force. Finally, it has been proved that the pull-in region can be completely suppressed. Since this approach does not require additional sensors or design changes, it is a promising cost-effective way to extend the mobility region of electromagnetic cantilevered actuators like microgrippers (Nonaka *et al.* 2004).

2.4 PZT

Piezoelectric actuators are ubiquitous in nanopositioning applications such as SPMs and micromotors. They have large operating bandwidth and can produce large mechanical forces in a compact design, which is particularly suitable for small amounts of power requirement. In addition, PZT actuators have been merged into drive systems for high speed valves for diesel injection, high resolution positioning of atomic force microscopes, high frequency vibration compensation, and so on.

Piezoelectric actuators are built with piezoelectric ceramic materials. The generally used ceramic material is the lead zirconate titanate ($Pb(Zr,Ti)O_3$) crystal which is commonly called the PZT. Being a polar material the ceramic possesses net external electric dipole moment which is caused by the alignment of numerous electric dipoles inside the crystal (Bassan *et al*. 2009). The individual electric dipoles in the ceramic material are randomly oriented when operated at temperature conditions that exceed the Curie temperature or in the insufficient of an applied electric field (Fig. 6 (a)). In this case, the ceramic material becomes unpolarized and paraelectric in nature, i.e., it loses the property of piezoelectricity. The individual crystals in the unpolarized ceramic material become symmetric in structure. Below the Curie temperature, the ceramic material undergoes a phase change and becomes ferroelectric in nature, i.e., the property of piezoelectricity is recovered. The phase change makes the individual crystals in the ceramic material be asymmetric in structure. When the ceramic material is subjected to large electric fields, the electric dipoles align themselves in a direction verge on the applied electric field. This causes the asymmetric axis of an individual crystal and all neighboring crystals to expand in a direction close to that of the applied electric field. This process is called polarization (Fig. 6 (b)). When the electric field is removed, the electric dipoles do not totally return to their original position. This phase of polarization is called remnant polarization where the ceramic remains partially polarized. In this phase, the net external electric dipole moment is not equal to zero. As shown in Fig. 6(b), the actuator will have some residual displacement. When electric field is re-applied, the ceramic material elongates and elongates the actuator (Fig. 6(c)) (Minase *et al*. 2010).

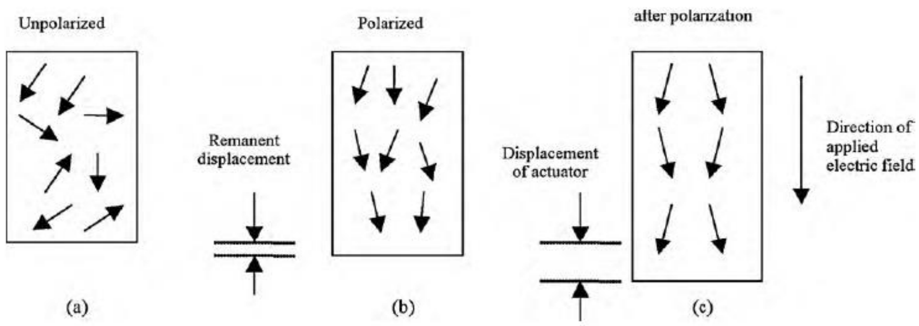

Fig. 6 Polarization process for a piezoelectric actuator (Devasia *et al*. 2007)

Piezoelectric actuators exhibit compact size, have excellent operating bandwidth, and can generate large mechanical forces using small amount of power. However, they provide a relatively small displacement range which blocks their applications in macropositioning. In many cases the inherent limited range of travel has been compensated for by the design of flexure amplification systems. When combined together, they provide precision motion free of friction and backlash, which is unattainable using conventional mechanical drives. Additionally, another major disadvantage of piezoelectric devices is their limited temperature operating range. They can be used for cryogenic applications but their maximum limit of operation is defined by the curie temperature of the PZT material. Above that temperature, the PZT substrate will be depoled, that is, its piezoelectric capabilities is lost. Even before this temperature is reached, the PZT will have started to depole. It is noticeable that PZT components can generate large amounts of heat when they operate at very high frequencies or when they are required to generate large forces (Logan *et al*. 2009).

2.5 SMA

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 (Ouyang *et al.* 2008). The SMA like NiTi is based on a unique capability of reversible plastic deformation. It can be allowed to attain certain shape of the material when heated and then, when cooled down, it can fully or partially recover its original shape (Varona *et al*. 2009).

At a low temperature, it seems that a SMA can be “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 through 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 specific alloy has excellent electrical and mechanical properties, long fatigue life, and high corrosion resistance (Ouyang *et al.* 2008).

However, due to the required Joule heating, SMA actuators suffer from the same limitations as electrothermal polysilicon devices in terms of high working temperatures and power consumption. Furthermore, SMAs are large in size with typical dimensions in the order of millimeter rather than micrometer. They exhibit poor efficiency and their displacement is not easy to control due to the significant hysteresis nonlinearity.

2.6 Summary

Among the different actuating principles employed for the design of microgrippers, the most popular actuators are based on electrostatic, electrothermal, PZT, and SMA approaches. Electrostatic actuators are the ones with the highest frequency response (up to hundreds of kHz under resonance) and the lowest power consumption, but their drawback is the need for relatively large voltages. On the other hand, electrothermal actuators operate with low voltages and offer large output force but its applicability in microgrippers is limited due to the high power consumption and high operating temperature that are unsuitable for biological and microrobotics uses. PZT actuator offers promising characteristics which includes high force to weight ratio, high operational bandwidth and upper temperature limit, zero backlash and coulomb friction, fast response, and unlimited motion resolution. Furthermore, extensive research efforts on piezoelectric actuator have focused on improving the control methodologies to achieve linear actuating system, which culminates into high accuracy and fidelity motions. But PZT has a relatively small displacement range and its limited temperature operating range. In contrast, SMA technology like NiTi is based on a unique capability of reversible plastic deformation that allows the material to attain certain shape when heated and then recover, fully or partially, its original shape when cooled down. However, SMA actuators suffer from the same limitations such as high working temperatures and power consumption due to the required Joule heating. A recent review of actuators for MEMS grippers was presented by Jia and Xu (2013).

3. Mechanism design

Microgripper mechanism is designed in consideration of actuator, sensor, and micro-objects to be grasped. This section describes some typical compliant mechanisms used for microgrippers.

Compliant mechanisms can be devised according to the desired input/output force/displacement requirements, including specified volume/weight, stiffness, and natural frequency constraints (Gao and Zhang 2012). As flexure is permitted in these mechanisms, they can be readily combined with unconventional actuation schemes, including thermal, electrostatic, piezoelectric, and SMA actuators.

A micro-motion system can be constructed as a closed-loop configuration or a parallel manipulator, which is based on the concept of compliant mechanism. The closed-loop configuration of the mechanism can provide better stiffness and accuracy, which is one of the major design goals for micro-motion systems. Besides, they allow the actuators to be fixed to the ground, which thus minimizes the inertia of moving parts (Ouyang *et al.* 2008). Some examples of compliant grippers are summarized as follows.

There are two popular approaches to design and analyze microgripper structures, that is, Pseudo Rigid Body Model (PRBM) and Finite Element Analysis (FEA). Usually, a combination of the two methods is employed to expedite the prototyping procedure which leads to the creation of high-performance mechanism. The preliminary modeling of the gripper is realized via the combination of PRBM and classical elastic theory. This approach aims to acquire fundamental understanding and graphical representation of the relative motion between the links and joints in order to generate optimum design configuration to meet the specifications. Model refinement is subsequently conducted utilizing FEA simulation. An Electro Discharge Machining (EDM) technique is usually employed to fabricate the gripper mechanism out of different materials. This technique is adopted due to its capacity to provide high accuracy cutting of intricate profiles such as odd-shape angle, complicated contours and cavities, etc. (Zubir *et al.* 2009). Some examples of compliant grippers are summarized as follows.

3.1 Structure of a piezoelectric-driven microgripper

Fig. 7 shows the 3-D drawing of a piezoelectric-driven microgripper designed by Wang *et al*. (2011). One can see from Fig. 7, the piezoelectric-driven microgripper includes the monolithic compliant mechanism (MCM), stack piezoelectric ceramic actuator (SPCA) (type: PTBS200, output displacement: 0–18 μm, applied voltage: 0–200 V), tip displacement sensor based on semiconductor strain gauges, gripping force sensor based on semiconductor strain gauges, base, cover plate, and baffle. The MCM is mounted on the base. One end of the SPCA is in contact with one end of the MCM and the other end is in contact with the baffle fixed to the base. It can provide a pretightening force to the MCM, which also can be adjusted by the screw. In addition, the cover is used to protect the microgripper.

The four-bar linkage mechanisms and parallelogram mechanisms are the basic components of the developed MCM for the microgripper, as shown in Fig. 8. The MCM is composed of the lever mechanisms (B_1CD and $B'_1C'D'$) based on the double-notch right circular flexure hinges and the parallelogram mechanisms ($A_1A_2A_3A_4$ and $A'_1A'_2A'_3A'_4$) based on the single-notch right circular flexure hinges, which are linked to the double-notch right circular flexure hinges at two ends of the links B_1B_2 and $B'_1B'_2$, respectively. The parallelogram mechanisms are used to further expand the output displacement of the lever mechanisms and to generate the parallel movement of the gripping jaws. In the MCM, the flexible beams connect the gripping jaws to the corresponding parallelogram mechanisms.

To grip an object, an applied voltage causes the SPCA to elongate and push the lever mechanisms (B_1CD and B'_1C'') of the MCM. This causes the gripping jaws to close to grip the object due to the deformation of the parallelogram mechanisms. Then, the power is switched OFF to return the SPCA to its initial position, which causes the gripping jaws to open and release the manipulated object under the elastic force of the flexure hinges.

3.2 Mechanism design of a 2-DOF modular microgripper

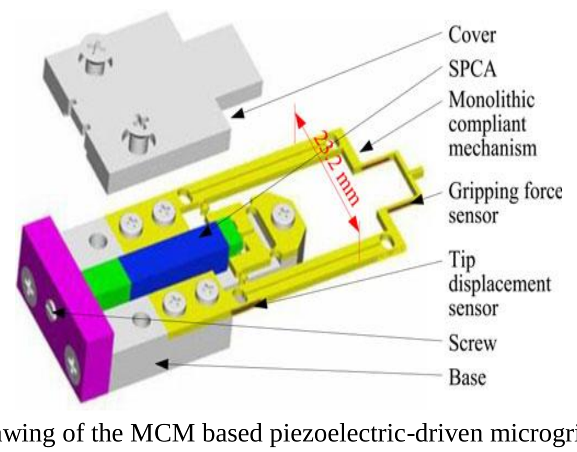

Fig. 7 Exploded 3-D drawing of the MCM based piezoelectric-driven microgripper (Wang *et al.* 2011)

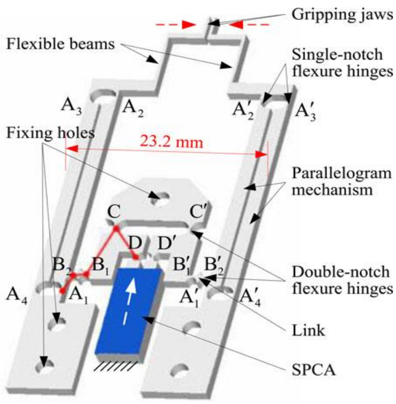

Fig. 8 3-D drawing of the MCM with an SPCA (Wang *et al.* 2011)

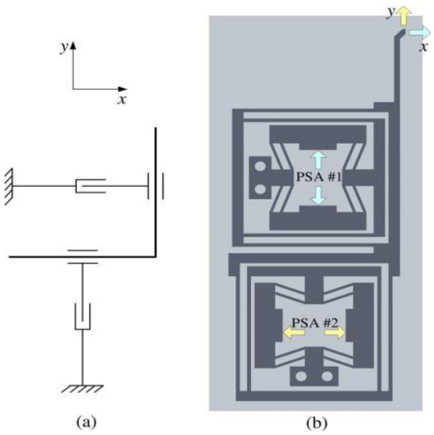

Fig. 9 (a) Scheme of a 2-PP parallel mechanism and (b) a 2-DOF microgripper arm driven by two PSAs (Xu 2012)

Recently, a 2-DOF XY stage is designed for each gripper arm by Xu (2012) to generate a 2-DOF microgripper with pure translation in both working directions. Furthermore, a two-prismatic-prismatic (2-PP) parallel mechanism (see Fig. 9(a)) is adopted to generate each gripper arm with decoupled translation along the two working axes. Considering the compactness requirement, an XY stage which is driven by two piezoelectric stack actuators (PSAs) is designed as shown in Fig. 9(b).

Moreover, the gripper arm as shown in Fig. 9(b) is considered as a basic module to construct a modular microgripper. For instance, a 2-DOF microgripper which is capable of performing the microgripping tasks in 2D plane is shown in Fig. 10. It includes two arms, each of which is capable of X and Y translations enabled by two PSAs. It is known that the conventional grippers can only transmit 1-DOF gripping motion with one arm or both arms actuated. Hence, the proposed 2-DOF gripper can perform more dexterous operation such as rolling objects (see inset in Fig. 10) in addition to the basic gripping manipulation, as compared with conventional grippers.

Besides, more than two arms can be employed to construct a 2-DOF microgripper for more dexterous operation in 3D space. For illustration, the modular microgrippers with three and four arms are shown in Fig. 11(a) and (b), respectively.

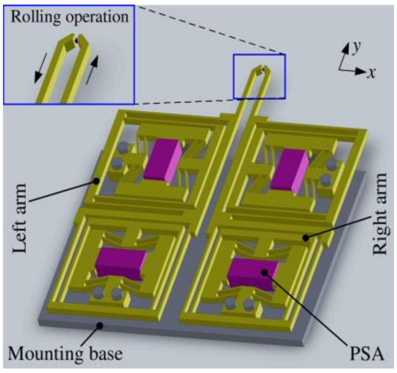

Fig. 10 A two-arm 2-DOF microgripper (Xu 2012)

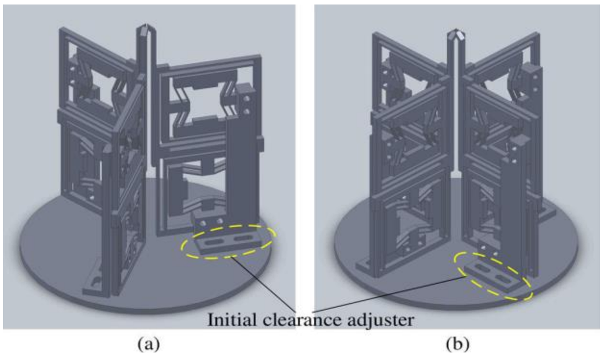

Fig. 11 (a) A three-arm and (b) a four-arm microgrippers (Xu 2012)

3.3 Active microgripper design

In addition, the active microgripper interface is designed to facilitate the replacement of active microgrippers that need to be manipulated by a robotic workstation to fulfill microassembly tasks. For example, Fig. 12 depicts a 3D sketch of the interface as proposed by Anis *et al.* (2006). The interface has three large pads which will be bonded to the robotic manipulator using standard tungsten probes firstly, and then electrically conductive adhesive. After that, the micro hinge structure is rotated by approximately 170^{o} angle till the hinge gold pad gets in contact with the small interface gold pad. Once this contact is achieved, the hinge will be fixed in place using adhesive. The interface, combined with the robotic manipulator, will be used to grasp an active microgripper and remove it off the surface of the chip. Additionally, a special interlocking mechanism will lock the microgripper in place, enabling it to fulfill its assembly tasks without slipping. To achieve the purpose of interchangeability, the microgrippers locks are designed, which can make the microgrippers easily installed and replaced.

Different parts of the structure are combined together through 2D springs, which unite the system into one large structure. These springs are designed to have very large electrical resistivity in order to reduce the flow of current between the pads. Additionally, their high flexibility will prevent the occurrence of any damage or fracture to the microgrippers as a result of thermal distortions which are caused during the bonding process (Dechev *et al*. 2003).

Moreover, a special active microgripper is designed, which is compatible with the proposed

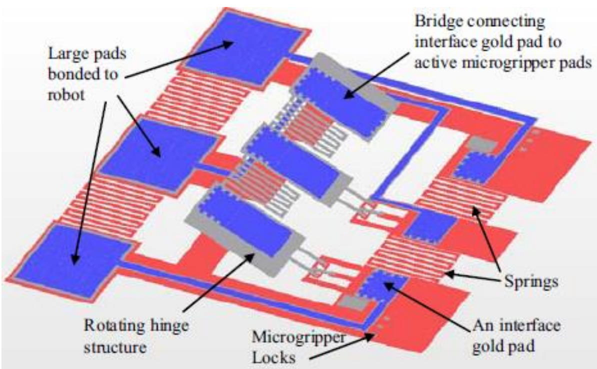

Fig. 12 3-D schematic drawing of the proposed interface (Anis *et al.* 2006)

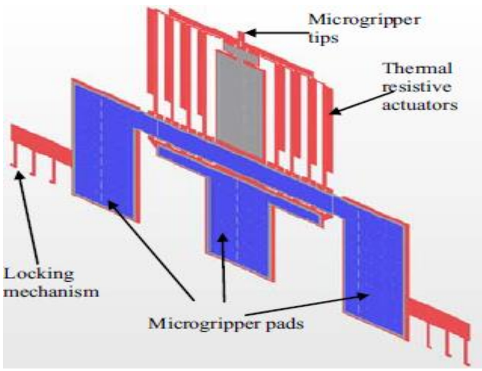

Fig. 13 Active microgripper (Anis *et al.* 2006)

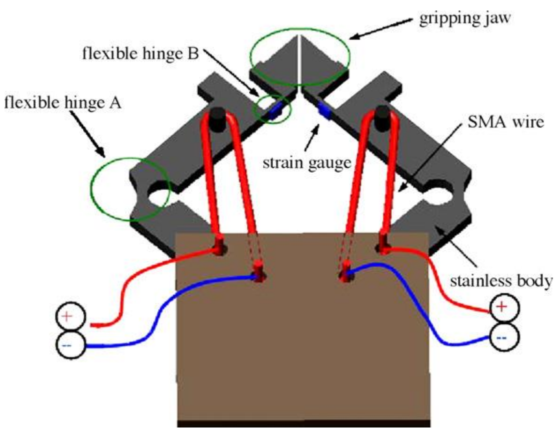

Fig. 14 Conceptual drawing of microgripper (Kyung *et al.* 2007)

interface. The microgripper in place added a locking mechanism when grasped by the interface. To grasp the microgripper, thin locks are designed to decrease the amount of force demanded by the interface. Fig. 13 shows an active microgripper that is compatible with the interface system.

3.4 Mechanism of a microgripper using SMA wires

Fig. 14 depicts a conceptual diagram of the microgripper as proposed by Kyung *et al*. (2007). The microgripper includes gripping jaws, SMA wires, two flexible hinges (A, B), a stainless body, and a strain gauge. The gripping jaw is used to operate the micro parts, with tips designed to open and close by up to 120 μm. The flexible hinge A is a rotating axis that transforms the linear motion of the SMA wire to a rotating motion. The flexible hinge B is made to be thinner than A in order to concentrate most of the gripping force, which is measured with a strain gauge. The SMA wire, which is the actuator, is composed of Ni–Ti alloy with a diameter of 100 μm to deal with the strength of hinge A and perform the fastest movement possible.

4. Sensors

Sensors play an important role in microgrippers. They operate based on a variety of techniques, such as inductive, piezoresistive, capacitive, and optical measurements. This section reviews two major types of sensors used in mirogrippers: displacement sensor and force sensor.

4.1 Displacement sensor

The position-sensing mechanism is determined by the speed and absolute positioning accuracy requirements of various nanopositioning systems. In this respect, we focus on two position-sensing techniques that are easily integrated with arrays of MEMS-based nanopositioning actuators, namely, capacitive position sensing and thermal position sensing.

Capacitive position sensors: Capacitive sensing is one of the most popular position-sensing techniques, which is in conjunction with microactuators to achieve nanometer resolution. The principle of capacitive position sensing is based on the movement of the shuttle electrode that causes a capacitance change between the fixed (stator) and the movable electrode (shuttle). The shuttle location relative to the stator can be determined by measuring the change in capacitance. The capacitance change due to shuttle movement offers an output voltage, which is a function of the shuttle's displacement after converted from capacitance to voltage through an electronic circuitry. It can be demonstrated that, for the comb-drive configuration, the output voltage and the shuttle displacement are linearly correlative. In addition, the sensing circuit design of capacitive position sensors is one of the most critical components (Devasia *et al*. 2007).

Thermal position sensors: The short, elongated U-shaped and free-standing cantilever are used in the basic design of the thermal position sensor. The devices are made from single-crystal Si using standard bulk micromachining technology. The sensing element is a resistive heater made from moderately doped Si and supported by legs made from highly doped Si that act as electrical leads. The voltage across the legs of the device is applied in a current flowing through the heater and a subsequent increase in the device temperature. To use this device as a displacement sensor, it should be positioned directly above an edge or step on the object of interest, with the long axis of the heater aligned parallel to the axis of motion (Devasia *et al*. 2007).

In addition, flexible displacement sensors generally have high stiffness. When such sensors are externally attached to soft actuators, they diminish the flexibility. Although some flexible displacement sensors have low stiffness, they are not adequate for practical use. The reason is that soft sensors such as artificial muscles generate an extending or a contracting deformation which involves high strain. This prevents soft sensors from enabling development of precise control systems with feedback (Kure *et al.* 2008).

4.2 Force sensor

The measurement of the micro-forces with extremely high sensitivity is required by recent advances of microassembly (Wang *et al*. 2008). Some force sensors are designed to operate in a manner analogous to scanning probe microscopy (SPM), which is widely utilized to study surface properties and topography of material. Force sensors are capable of resolving micro-Newton (μN) level forces which are typically encountered when manipulating biological cells and micro parts. The sensors are generally made using microfabrication techniques (Cappelleri *et al.* 2011).

The force sensor is used to guarantee the robustness and reliability of the microassembly process by providing real-time force feedback. In general, piezoresistive and capacitive sensors are used extensively as force sensors because of their simple structure and simple principle of operation. Piezoresistive force sensors have been utilized not only to measure the contact micro-forces in a micromanipulation system (Lu *et al*. 2007), but also been used in a robotic macro-manipulation system (Shen *et al.* 2006).

But majority of commercially available micro-force sensors are only capable of measuring one dimensional forces and requires extensive hardware, software, as well as, in some cases, a high resolution scanning electron microscope to function. What's more, the disadvantage of piezoresistive sensors are the large temperature drift, large power consumption, and the very strict requirement of placing the sensing resistors accurately to obtain maximal sensitivity. A state-of-the-art survey of MEMS gripper sensors was conducted by Jia and Xu (2013).

The electronics, power, and mechanical noises are the greatly restricted condition in the sensitivity and resolution of capacitive sensors. Unlike piezoresistive and capacitive sensors, resonant force sensors are designed to overcome some of the drawbacks. Resonant sensors can provide high resolution, transduction sensitivity, performance, long-term stability, and reliability. The stability of the sensor is determined by the mechanical properties of the resonator material rather than affected by the stability of the electronics (Bahadur *et al*. 2005).

5. Control techniques

In microgrippers, position control and force control are the two main concerned techniques. Position control includes various methods such as PID control. The most useful methods in force control are impedance control and stiffness control (Xu 2013a, Xu 2013b). For microgrippers, the availability and choice of actuators and sensors are important issues in the design of controllers. Taking piezoelectric actuators as example, this part reviews the literature on controller development. A piezoelectric actuator is generally driven by a voltage source (Goldfarb and Celanovic 1997). Nevertheless, a voltage driven piezoelectric actuator exhibits hysteresis and creep. It has been shown that the phenomena of hysteresis and creep of a piezoelectric actuator can be minimized by driving the actuator using a charge input or by inserting a capacitor in series with a voltage driven actuator (Minase *et al.* 2010).

5.1 Voltage driven scheme

An easy way to drive a piezoelectric actuator is to use a voltage input (Goldfarb and Celanovic 1997). The operating range and bandwidth of a piezoelectric actuator will not be reduced by using voltage drives. But the disadvantage comes along with it, that is, the effects of hysteresis and creep

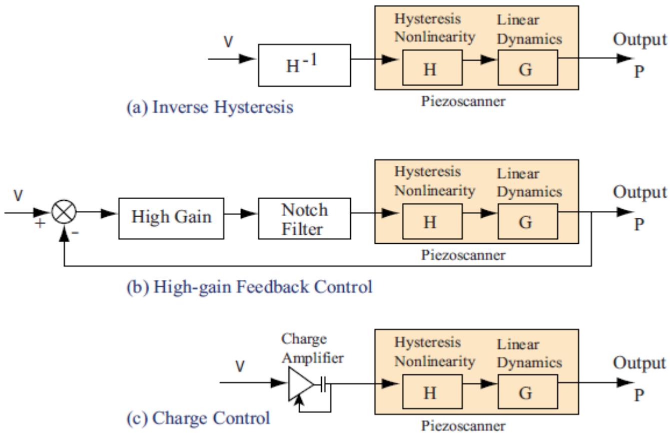

Fig. 15 Three different approaches to linearize hysteresis nonlinearity in piezoscanners (Clayton *et al.* 2009)

(Goldfarb and Celanovic 1997). They affect the precise positioning when using a voltage-driven piezoelectric actuator.

To reduce the positioning errors caused by inaccurate prediction of hysteresis and creep, a robust controller is needed. In addition, the controller could be used to reduce the positioning error effectively due to vibrations generated when a piezoelectric actuator is driven at a frequency close to its resonance. A piezoelectric actuator driven positioning system can be accurately positioned by using numerous feedback control schemes proposed in the literature (Lu *et al.* 2006, Song *et al.* 2005). Besides, precise positioning of a piezoelectric actuator using open-loop control has also been widely demonstrated (Minase *et al.* 2010).

The hysteresis nonlinearity is typically linearized by using inversion technique to obtain the feedforward input (Ali *et al*. 2011). For instance, inversion based hysteresis compensation, which can linearize the piezoscanner dynamics for SPM control, has been demonstrated. As can be seen in Fig. 15(a), such an inversion-based feedforward can amend for hysteresis effects with high precision. Yet, the drawback is the substantial modeling complexity. Another way to reduce the hysteresis effects is to make use of high gain feedback. In this way as shown in Fig. 15(b), the gain margin of the system can be increased by using notch filters (Leang and Devasia 2002). As a result, higher gain margin permits the use of higher-gain feedback, which substantially reduces the hysteresis nonlinearity (Clayton *et al*. 2009).

5.2 Charge driven scheme

Instead of voltage input, another way to reduce hysteresis and creep is to drive a piezoelectric actuator using a charge input as shown in Fig. 15(c), which can reduce the hysteresis nonlinearity. The charge control approach has been applied to SPM successfully (Clayton *et al*. 2009). Also, it can be easily implemented and it obviates the need for detailed hysteresis modeling and inversion. Furthermore, it is possible to eliminate the requirement on position sensing and feedback. When connected electrically, the actuator which is a dielectric acts like a non-linear capacitor can changes its capacitance even when the input voltage is kept constant (Goldfarb and Celanovic

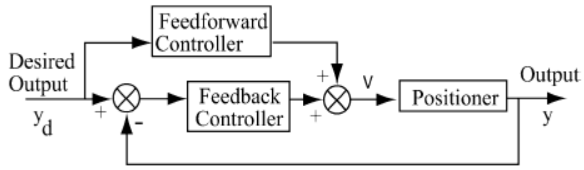

Fig. 16 Control scheme augmenting feedback with feedforward (Clayton *et al*. 2009)

1997). The change in the capacitance leads to a change in the amount of the charge acting on the actuator. This causes hysteresis and creep. Regulating the current and hence the charge prevents the actuator from changing its capacitance, thus, leads to a significant reduction in hysteresis and creep (Goldfarb and Celanovic 1997). Therefore, a charge input gives rise to approximately linear operation of a piezoelectric actuator (Minase *et al.* 2010).

5.3 Integration of feedforward and feedback controllers

Feedforward control improves performance without incurring the stability problems associated with feedback design. However, it cannot account for modeling errors. In particular, inversion-based feedforward controllers (which are model-based) cannot correct for tracking errors due to plant uncertainties (Xu 2013c). Therefore, it is necessary to use feedback in conjunction with feedforward to reduce uncertainty-caused errors in the inverse input as shown in Fig. 16. Note that the use of feedforward inputs can improve the tracking performance as compared with the use of feedback alone, even in the presence of plant uncertainties.

In most cases, noise and vibrations are the main factors reducing the actuation and sensing performances of micromanipulation systems in terms of a low repeatability and a loss of accuracy. Moreover, when end effectors are used as sensors, vibrations are reflected in the sensor output as a measurement noise reducing significantly the sensing resolution. When a high positioning accuracy is needed, this noise one has to be dealt with. Numerous solutions are possible: designing environmental isolation platforms, considering noise limitation during the design of micromanipulation systems by an appropriate choice of the resonance frequency of end effectors, or using appropriate controllers for noise rejection. Multi-noise isolation platforms are generally very expansive and have a limited volume. Moreover, vibration isolation tables commonly found in typical microrobotics laboratories allow efficient ground noise filtering but fail to filter acoustic noises. Then, the use of appropriate controllers for noise rejection is an interesting and low cost solution when considering a large kind of microgrippers. For this purpose, defining appropriate control strategies requires understanding the sources of noise and the manner in which they act on the process. Moreover, the noise has to be considered differently according to the dimensions of the micromanipulation system (Boundaoud *et al*. 2011).

6. Conclusions

This paper presents an overview of the recent developments on flexure-based compliant microgrippers. Basically, a satisfactory microgripper must be able to firmly hold the object of interest with a sufficiently high force to keep it within the grips but at the same time low enough to avoid damaging either the gripper tips or grasped object. Generally, the electronic actuators have high frequency response and low power consumption. But their limits come from the size and the operating temperatures. On the other hand, PZT and SMA actuators have advantages of high resolution positioning and high frequency vibration compensation. However, they have some limitations in terms of relatively small displacement range and high required working temperature. Compliant mechanisms can be devised to achieve the desired input/output force/displacement characteristics, including the specified volume/weight, stiffness, and natural frequency constraints. As flexure is permitted in these mechanisms, they can be readily combined with unconventional actuation schemes, including thermal, electrostatic, piezoelectric, and SMA actuators. Effective mechanical microgripper should possess three main characteristics: (1) the ability to steadily grasp objects of different shape; (2) not incurring damage to the micro objects; (3) high positioning accuracy. These characteristics can be well satisfied by the compliant mechanism design. By using the compliant mechanism, microgrippers can be designed with merits such as the ability to gently grasp objects with different shapes, high positioning accuracy, and sufficient number of degrees of freedom. In addition to the choice of actuators and mechanisms, different sensors and control methods can be chosen to improve the stability and the accuracy for pertinent applications.

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References

Albrecht, T., Despont, M., Eleftheriou, E., Bu, J.U. and Hirano, T. (2004), “MEMS in mass storage systems”, *Enabling Technologies for MEMS and Nanodevices*, Germany, Wiley, Vol. 1, 193-236.

Amjad, K., Bazaz, S.A. and Lai, Y. (2008), “Design of an electrostatic MEMS microgripper system integrated with force sensor”, *Proceedings of the IEEE International Conference on Microelectronics*, 236-239.

Anis, Y.H., Mills, J.K. and Cleghorn, W.L. (2006), “Active microgripper interface used in microassembly of MEMS”, *Proceedings of the Canadian Conference on Electrical and Computer Engineering*, 352-354, Ottawa, May.

Ali, N., Shakoor, R.I. and Hassan, M.M. (2011), “Design, modeling and simulation of electrothermally actuated microgripper with integrated capacitive contact sensor”, *Proceedings of the 14th IEEE International Conference on Multitopic*, 201-206.

Bassan, H.S., Patel, R.V. and Moallem, M. (2009), “A novel manipulator for percutaneous needle insertion: Design and experimentation”, *IEEE/ASME Transactions Mechatronics*, **14**(6), 746–761, Dec.

Bahadur, I.B., Mills, J. and Sun, Y. (2005), “Design of a MEMS-based resonant force sensor for compliant, passive microgripping”, *Proceedings of the IEEE International Conference on Mechatronics and Automation*, **1**, 77-82.

Baillieul, J. and Weibel, S. (1998), “Scale dependence in the oscillatory control of micromechanisms”, *Proceedings of the 37th IEEE Conference on Decision and Control*, **3**, 3058-3063.

Brinkerhoff, R. and Devasia, S. (2000), “Output tracking for actuator deficient/ redundant systems: multiple piezoactuator example”, *AIAA J. Guid. Control Dyn.*, **23**(2), 370-373.

Barrett, R.C. and Quate, C.F. (1991), “Optical scan-correction system applied to atomic force microscopy”, *Rev. Sci. Instrum.*, **62**(6), 1393-1399.

Boundaoud, M., Haddab, Y., Le Gorrec, Y. and Lutz, P. (2011), "Noise characterization in millimeter sized micromanipulation systems", *Mechatronics*, **21**, 1087-1097.

Cappelleri, D.J., Piazza, G. and Kumar, V. (2011), "A two dimensional vision-based force sensor for microrobotic applications", *Sensor. Actuat. A*, **171**(2), 340-351.

Chien, C.H., Wu, Y.D., Chiou, Y.T., Hsieh, C.C., Chen, Y.C., Chen, T.P., Tsai, M.L. and Wang, C.T. (2006), "Nanoscale deformation measurement by using the hybrid method of gray-level and holographic interferometry", *Opt. Lasers Eng.*, **44**(1), 80-91.

Croft, D., Shedd, G. and Devasia, S. (2001), "Creep, hysteresis, and vibration compensation for piezoactuators: atomic force microscopy application", *Proceedings of the American Control Conference*, **3**, 2123-2128.

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", *J. Dyn. Syst. Measurement Control*, **131**(6), 061101-1 - 061101-19.

Cuttino, J.F., Miller, A.C. and Schinstock, D.E. (1999), "Performance optimization of a fast tool servo for single-point diamond turning machines", *IEEE-ASME T. Mech.*, **4**(2), 169-179.

Chang, T. and Sun, X. (2001), "Analysis and control of monolithic piezoelectric nano-actuator", *IEEE T. Control Syst. Tech*., **9**(1), 69-75.

Dechev, N., Cleghorn, W.L. and Mills, J.K. (2003), "Microassembly of 3-D MEMS structures utilizing a MEMS microgripper with a robotic manipulator", *Proceedings of the IEEE International Conference on Robotics and Automation*, **3**, 3193-3199.

Devasia, S., Eleftheriou, E. and Moheimani S.O.R. (2007), "A survey of control issues in nanopositioning", *IEEE T. Control Syst.Tech.*, **15**(5), 802-823.

Goldfarb, M. and Celanovic, N. (1997), "A lumped parameter electromechanical model for describing the nonlinear behaviour of piezoelectric actuators", *J. Dyn. Syst. – T. ASME*, **119**(3), 478-485.

Hamedi, M., Salimi, P. and Vismeh, M. (2012), "Simulation and experimental investigation of a novel electrostatic microgripper system", *Microelectron. Eng.*, **98**, 467-471.

Hung, E.S. and Senturia, S.D. (1999), "Extending the travel range of analog- tuned electrostatic actuators", *J. Micoroelectromech. Syst.*, **8**(4), 497-505.

Horenstein, M.N., Bifano, T.G., Mali, R.K. and Vmdelli, N. (1997), "Electrostatic effects in micromachined actuators for adaptive optics", *J. Electrostat.*, **42**(1), 69-81.

Jia, Y. and Xu, Q. (2013), "MEMS microgripper actuators and sensors: the state-of-the-art survey", *Recent Patent. Mech. Eng.*, **6**(2), 132-142.

Kyung, J.H., Ko, B.G., Ha, Y.H. and Chung, G.J. (2007), "Design of a microgripper for micromanipulation of microcomponents using SMA wires and flexible hinges", *Sensor. Actuat. A*, **141**(1), 144-150.

Kim, K., Liu, X., Zhang, Y. and Sun, Y. (2008), "Micronewton force-controlled manipulation of biomaterials using a monolithic MEMS microgripper with two-axis force feedback", *Proceedings of the IEEE International Conference on Robotics and Automation*, 3100-3105, May.

Kure, F., Kanda, T., Suzumori, K. and Wakimoto, S. (2008), "Flexible displacement sensor using injected conductive paste", *Sensor. Actuat. A*, **143**(2), 272-278.

Lu, Z., Chen, P.C.Y. and Lin, W. (2006), "Force sensing and control in micromanipulation", *IEEE T. Syst. Man Cy. C*, **36**(6), 713-724.

Lu, Z., Chen, P.C.Y., Nam, J., Ge, R. and Lin, W. (2007), "A micromanipulation system with dynamic force-feedback for automatic batch microinjection", *J. Micromech. Microeng.*, **17**(2), 314-321.

Logan, D., Ahearme, E. and Byrne, G. (2009), "Piezoelectric drive systems in ultraprecision machines: a review of the state-of-the-art", *Int. J. Comput. Mater. Sci. Surface Eng.*, **2**(1-2), 54-62.

Leang, K. and Devasia, S. (2002), "Hysteresis, creep, and vibration compensation for piezoactuators: feedback and feedforward control", *Proceedings of the Second IFAC Conference on Mechatronic Systems*, Berkeley, CA, 283-289, Dec.

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", *Precis. Eng.*,

34(4), 692-700.

Nonaka, K., Sakai, K. and Baillieul, J. (2004), "Open loop oscillatory control for electromagnetic actuated microgrippers", *Proceedings of SICE Annual Conference*, **3**, 2285-2290.

Nonaka, K. and Baillieul, J. (2001), "Open loop robust vibrational stabilization of a two wire system inside the snap-through instability region", *Proceedings of the 40th IEEE Conference on Decision and Control*, **2**, 1334-1341.

Ouyang, P.R., Tjiptoprodjo, R.C., Zhang, W.J. and Yang, G.S. (2008), "Micro-motion devices technology: the state of arts review", *Int. J. Adv. Manuf. Tech.*, **38**(5-6), 463-478.

Okazaki, Y. (1990), "A micro-positioning tool post using a piezoelectric actuator for diamond turning machines", *Precis. Eng.*, **12**(3), 151-156.

Pedrak, R., Ivanov, T., Ivanova, K., Gotszalk, T., Abedinov, N., Rangelowa, I.W., Edinger, K., Tomerov, E., Schenkel, T. and Hudek, P. (2003), "Micromachined atomic force microscopy sensor with integrated piezoresistive, sensor and thermal bimorph actuator for high-speed tapping-mode atomic force microscopy phase-imaging in higher eigenmodes", *J. Vac. Sci. Technol. B*, **21**(6), 3102-3107.

Sugimoto, T., Nonaka, K. and Horenstein, M.N. (2005), "Bidirectional electrostatic actuator operated with charge control", *J. Microelecromech. S.*, **14**(4), 718-724.

Seeger, J.I. and Boser, B.E. (2003), "Charge control of parallel-plate, electrostatic actuators and the tip-in instability", *J. Microelecromech. S.*, **12**(5), 656-671.

Schneir, J., McWaid, T.H., Alexander, J. and Wilfley, B.P. (1994), "Design of an atomic-force microscope with interferometric position control", *J. Vac. Sci. Technol. B*, **12**(6), 3561-3566.

Shen, Y., Winder, E., Ning, X., Pomeroy, C.A. and Wejinya, U.C. (2006), "Close-loop optimal control-enabled piezoelectric microforce sensors", *IEEE-ASME T. Mech.*, **11** (4), 420-427.

Song, G., Zhao, J., Zhou, X. and Abreu-Garcia, J.A.D. (2005), "Tracking control of a piezoceramic actuator with hysteresis compensating using inverse preisach model", *IEEE-ASME T. Mech.*, **10**(2), 198-209.

Tang, W.C., Nguyen, T.H., Judy, M.W. and Howe, R.T. (1990), "Electrostatic-comb drive of lateral polysilicon resonators", *Sensor. Actuat. A*, **21**(1-3), 328-331.

Varona, J., Saenz, E., Fiscal-Woodhouse, S. and Hamoui, A.A. (2009), "Design and fabrication of a novel microgripper based on electrostatic actuation", *Proceedings of the IEEE International Midwest Symposium on Circuits and Systems*, 827-832.

Wang, L., Mills, J.K. and Cleghorn, W.L. (2008), "Development of an electron tunneling force sensor for the use in microassembly", *Proceedings of the IEEE International Conference on Microsystems and Nanoelectronics Research*, 205-208.

Wang, D.H., Yang, Q. and Dong, H.M. (2011), "A monolithic compliant piezoelectric-driven microgripper: design, modeling, and testing", *IEEE-ASME T. Mech.*, **18**(1), 138-147.

Xu, Q. (2012), "Mechanism design and analysis of a novel 2-dof compliant modular Microgripper", *Proceedings of 7th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 1966-1971.

Xu, Q. (2013a), "Adaptive discrete-time sliding mode impedance control of a piezoelectric microgripper", *IEEE T. Robot.*, **29**(3), 663-673.

Xu, Q. (2013b), "Precision position/force interaction control of a piezoelectric multimorph microgripper for microassembly", *IEEE T. Autom. Sci. Eng.*, **10**(3), 503-514.

Xu, Q. (2013c), "Identification and compensation of piezoelectric hysteresis without modeling hysteresis inverse", *IEEE T. Ind. Electron.*, 6**0**(9), 3927-3937.

Zhou, H., Tan, K.K. and Lee, T.H. (2000), "Micro-positioning of linear piezoelectric motors based on a learning nonlinear PID controller", *Proceedings of the 39th IEEE Conference on Decision and control*, **1**, 913-918.

Zubir, M.N.M., Shirinzadeh, B. and Tian, Y. (2009), "A new design of piezoelectric driven compliant-based microgripper for micromanipulation", *Mech. Mach. Theory*, **44**(12), 2248-2264.

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