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A microgripper using piezoelectric actuation for micro-object manipulation

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Abstract

Design, fabrication and tests of a monolithic compliant-flexure-based microgripper were performed. The geometry design and the material stresses were considered through the finite element analysis. The simulation model was used to study in detail profiles of von Mises stresses and deformation. The maximum stress in the microgripper is much smaller than the critical stress values for fatigue. The microgripper prototype was manufactured using micro-wire electrode discharge machining. A displacement amplification of 3.0 and a maximum stroke of 170 μm were achieved. The use of piezoelectric actuation allowed fine positioning. Micromanipulation tests were conducted to confirm potential applications of the microgripper with piezoelectric actuation in handling micro-objects. The simulation and experimental results have proven the good performance of the microgripper.

Keywords: Gripper; Actuator; Manipulation; Piezoelectric actuation

1. Introduction

Gripping and manipulating micro-objects is required for a wide range of important applications such as the assembly of micro-parts to obtain miniature systems or component assembly in electronics packages [1]. An effective mechanical micromanipulator should possess the ability to grasp objects of different shapes steadily with high positioning accuracy. The manipulators should be able to accurately control grasping forces in order to avoid any damage to the small-size delicate objects, which are less than 1 mm in diameter.

Over the years, micro-scale technologies have been developed for consumer products and specialized applications in electronics, information technology, optics, medicine and biology covering areas such as diagnostics, drug delivery, tissue engineering and minimally invasive surgery [2–5]. Although considerable developments have been achieved in fabrication of micro-parts, the assembly of these micro-systems still accounts for a substantial portion of the final cost.

A microgripper is one of the key elements in micro-robotics and micro-assembly technologies for handling and manipulating micro-objects without damage. An essential component of all microgrippers is the actuator, which provides the required applied force to make the device operate as a gripper. Various prototypes of microgrippers of different actuation methods have been developed, including electrothermal actuators [6–9], electrostatic actuators [10–15], piezoelectric actuators [16,17], electromagnetic actuators [18] and shape memory alloy actuators [19–21].

Microgripping is different from conventional gripping. Micro-parts with major dimensions less than 100 μm are often fragile and can be easily damaged during gripping, and thus special grasping techniques are required. A miniature gripper may be of interest to achieve safe transport of small objects such as electronic devices, and to have a new end-effector tool to grasp cells for bio-application as well as for endoscope manipulations. The specifications to realize such a gripper are quasi-static motion to have high accuracy in micro-positioning, a large-stroke to grasp the maximum types of object, and the use of special actuation method like piezoelectric actuation [22].

Piezoelectric actuators are widely used in various applications [23–33] as well as in microgrippers, because of their

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advantages [34]: large generated force, stable displacement, high response speed and ease of use.

In this study, design, fabrication and tests of a monolithic compliant-flexure-based microgripper were performed. The geometry design and the material stresses were considered through the finite element analysis. The simulation model was used to study in detail profiles of von Mises stresses, deformation and contact forces. A microgripper prototype was fabricated using micro-wire electrode discharge machining. Micromanipulation tests were carried out to confirm the potential applications of the microgripper with piezoelectric actuation in handling micro-objects.

2. Design and fabrication of the microgripper

The micromanipulation solution is a monolithic compliant mechanism (shown in Fig. 1). The dimensions of the microgripper were designed in such a way that micro-manufacturing technologies could be used, leading to low cost and an easy adaptation to different micromanipulation needs. The microgripper was also large enough to manipulate components with dimensions range from a few microns to hundreds of microns. The design enables the microgripper tips to move in parallel and thus to be always mutually aligned.

The compliant mechanism moves solely by deformation and by utilizing its flexural hinges instead of conventional bearings, joints and gears. The absence of conventional joints and bearing surfaces produces a clean device that is free of lubricants or other contaminants, and therefore it can be used in clean environments. The design uses flexures and the motion created is a result of the strain of the elastic linkages [35].

The microgripper compliant mechanism was designed to be flexible and its motion transfer function was made possible by the elastic deformation of the flexible elements. The mechanism is used to amplify the initially small actuating displacement in order to achieve larger output displacements. The compliant amplification mechanism combined with a solid-state piezoelectric translator can yield a microgripper with good bandwidth, force and stroke control. For general micromanipulation, this microgripper can be actively controlled to open and close their tips. Actively controlled microgrippers are well suited for grasping irregular objects in both static and dynamic environments.

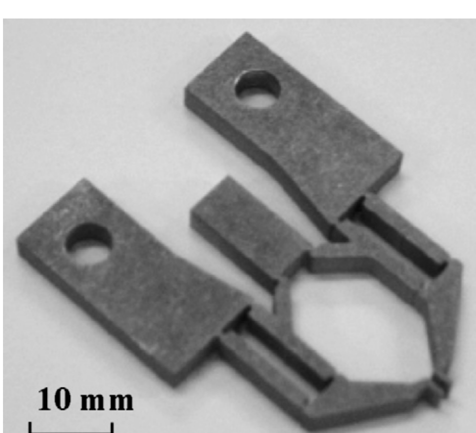

Fig. 1. The microgripper designed and fabricated.

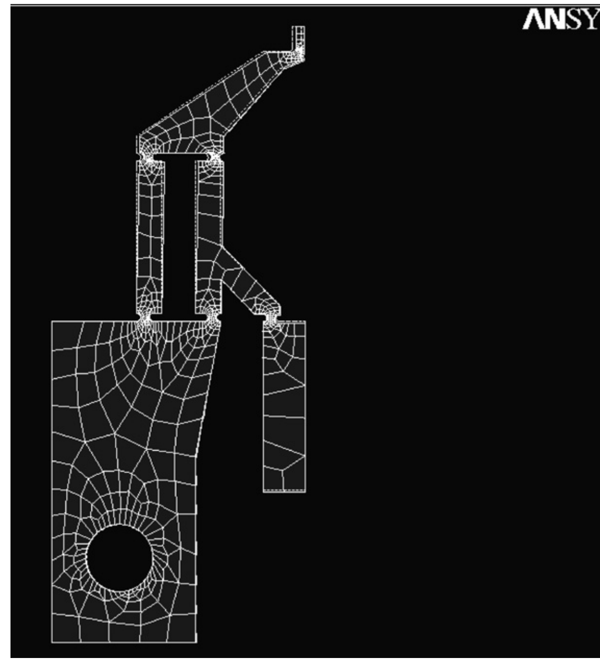

Fig. 2. FEA model of an half of the mechanism.

The microgripper was manufactured from a single piece of spring steel using a micro-wire electrical discharge machine (EDM). Another material used to fabricate it was aluminium. These materials were selected because they are common engineering materials and are easy to be machined by EDM.

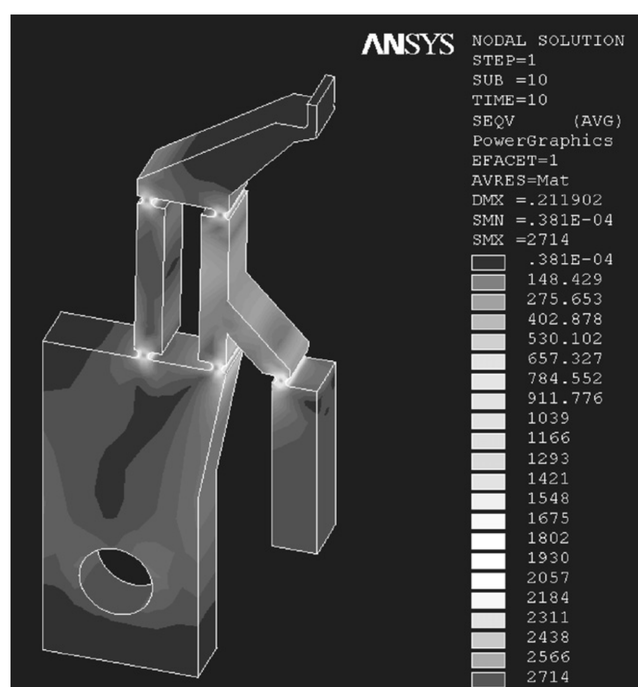

Fig. 3. Stress concentration occurs at the notch hinge points (the unit of the stress in the figure is kPa).

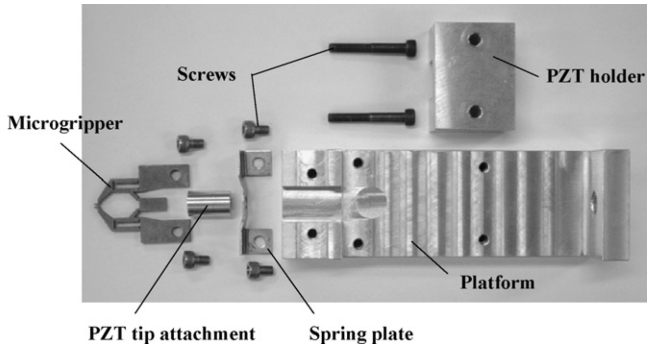

Fig. 4. Components of the gripping device.

The micro-wire EDM technology can generate the microgripper with good manufacturing precision. With achievable dimensional tolerances of ±5 μm, a surface roughness of about 0.1 μm and the capability to use Ø20 μm wires, the wire cutting method is suitable for micro and high precision machining. The microgripper prototype is 36 mm long, 30 mm wide and 3 mm thick.

3. Finite element analysis

Finite element analysis (FEA) was performed to investigate the compliant mechanism. 2D and 3D elements were used to model the microgripper mechanism and predict the amplification ratio, stress concentration and displacements of the microgripper mechanism. Fig. 2 shows the finite element model of the microgripper. The material properties used for the FEA of the microgripper are that of spring steel or aluminium. The bulk stress concentration occurs at the notch hinge points as shown in Fig. 3. The maximum stress found is 2.1 MPa, which is much smaller than the yield stress and the elastic modulus of the material.

4. Prototype of the gripping device

The fabricated microgripper itself is still not a functional device. It is necessary to attach it to a fixture, connect it with an actuator and position it on the operating platform. Only then it is ready for utilization. The components required for the gripping device are shown in Fig. 4.

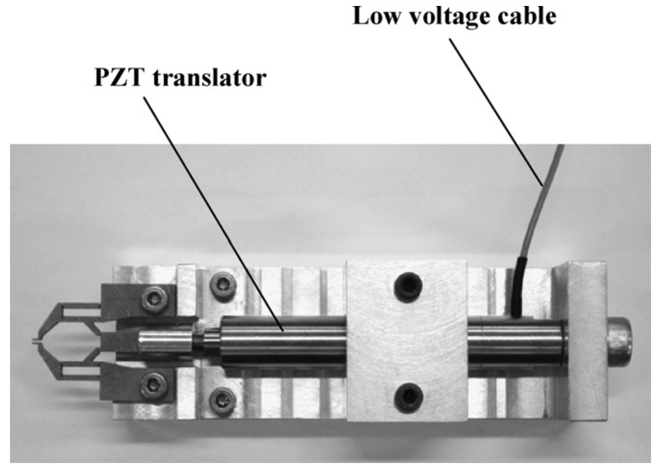

Fig. 5. The prototype of the gripping device with a PZT translator.

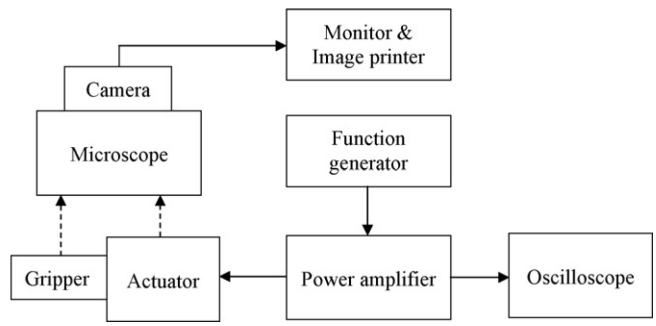

Fig. 6. Schematic diagram of the experimental setup for testing of the PZT actuator and the microgripper.

Previous work [36–38] indicates that piezoelectric ceramics, coupled with an appropriate transmission, can provide the desired actuation performance. Typical lead–zirconate–titanate (PZT) piezoelectric actuators can perform step movements with a resolution on the order of a nanometer. These actuators offer open-loop stable operation with the power and bandwidth necessary for the specified motion. However, the limitation of the piezoelectric material is that only a typical strain of 0.1% is achievable, thus limiting its actuation stroke.

This research work attempts to overcome this limitation of the PZT actuator by the amplification mechanism. The advantage of this method is that the grasp of an object can be perfectly controlled because the actuation of the gripper can be controlled

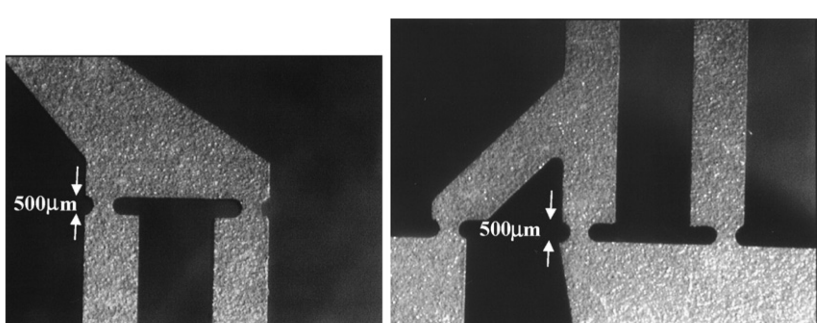

Fig. 7. Inspection of the notch hinge and linkage features.

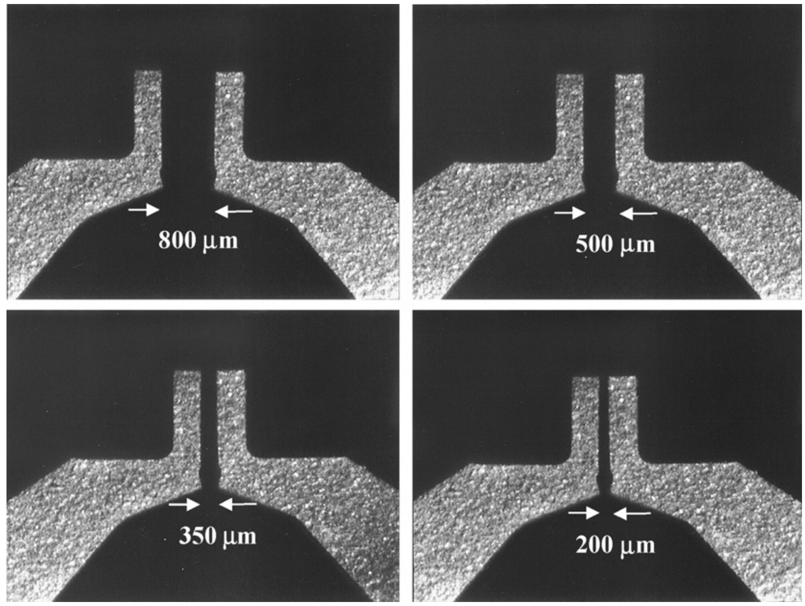

Fig. 8. Various displacement modes of the microgripper.

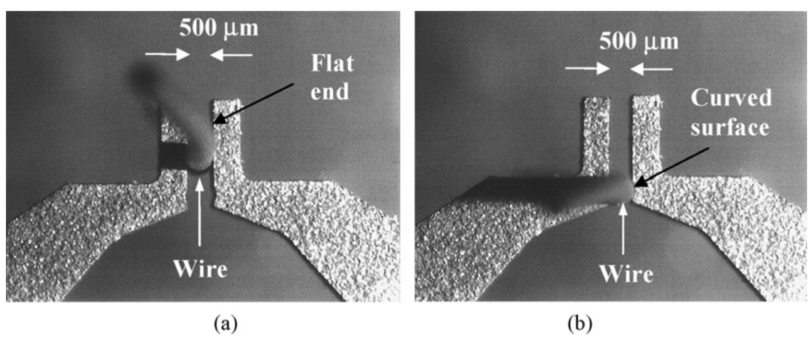

Fig. 9. A vertical Teflon wire gripped by (a) the flat ends or (b) the curved surfaces of the microgripper.

and stopped at any time. Thus, it allows the microgripper to close its tips in the desired position. This is useful to achieve a secure transport or immobilize an object without damaging it.

The prototype of the gripping device is shown in Fig. 5. A piezoelectric actuator (Model LVPZT P-842 from Physik Instru-

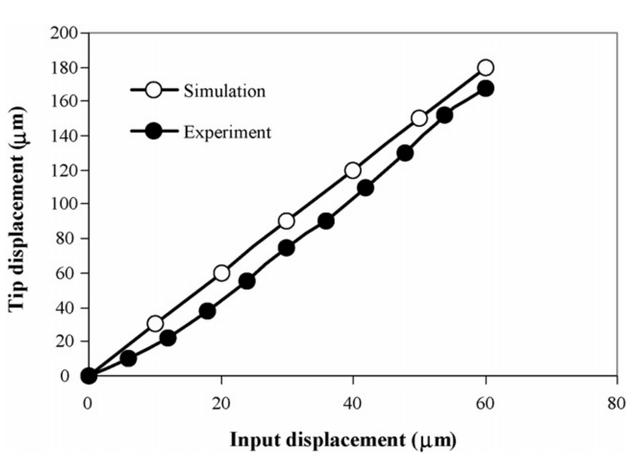

Fig. 10. The tip displacements of the microgripper obtained from the FEA simulations and the experiments.

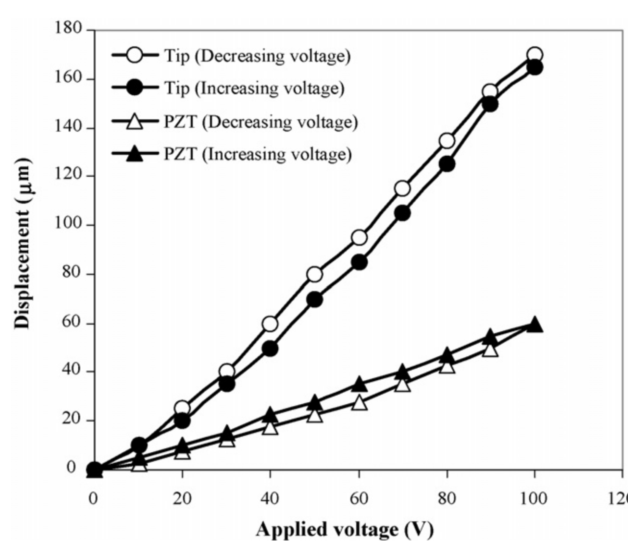

Fig. 11. Displacements of the PZT actuator and the gripper tip vs. the applied voltage to the actuator.

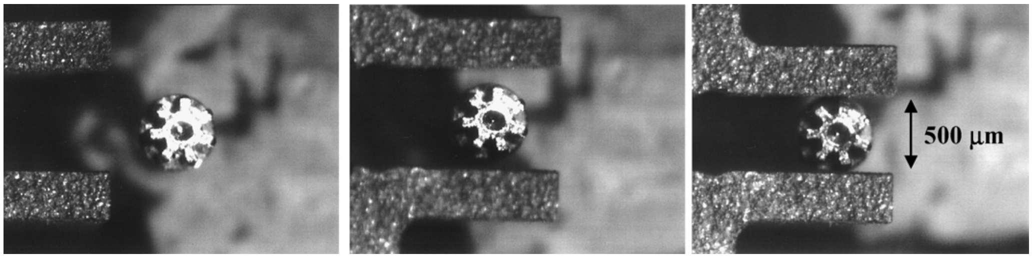

Fig. 12. Grasping action of the microgripper on the miniature gear.

mente) was combined with the microgripper to achieve precise grasping motion due to its very fine positioning feature. The PZT actuator functions with a typical open-loop at an operating voltage of 0–100 V. The lifetime of the PZT actuator is not limited by wear and tear. Tests have shown that the PZT actuators can perform billions of cycles without any loss of performance, if they are operated under suitable conditions [39]. The PZT translator used for the tests is a high-resolution linear actuator suitable for static and dynamic applications. The translator is equipped with highly reliable multilayer PZT ceramic stacks protected by a non-magnetic stainless steel case with internal spring preload. The maximum displacement provided by the translator is 60 μm. It is electronically controlled by an amplifier unit.

5. Performance testing

Fig. 6 shows the experimental setup including measuring devices for testing of the PZT actuator and the microgripper. The experimental setup consisted of the micro-gripping device, the amplifier unit used to drive the PZT translator and an optical microscope linked to a monitor for the measurement of the displacements on the microgripper. The displacements of the PZT actuator were measured using a microscope with a CCD camera attached. The images of the displacements were captured and the displacements were measured. Additionally, some gripping tasks were performed using this setup.

Under the normal condition, the microgripper is in its closed position. External actuation is used for opening the tips of the microgripper and offsetting the gripping force of the microgripper to prevent damage to delicate objects.

Before testing, a visual inspection of the microgripper was conducted using the optical microscope to verify the feature sizes of the prototype. The flexural notch hinges and the linkages were observed as shown in Fig. 7.

During the functional testing of the prototype, actuation of the microgripper by hand was performed, as well as actuation using the PZT translator, to check kinematical correctness of the gripper. The displacement modes of the microgripper tips obtained using actuation by hand are shown in Fig. 8. The size range of the part that can be grasped using this microgripper is 200–800 μm.

Using piezoelectric actuation, it is possible to perform controlled opening and closing of the microgripper tips. The microgripper is actuated by the translating motion. A movement forward towards the microgripper tip is transformed by the compliant mechanism kinematics into the tip opening. Retraction of the PZT actuator closes the microgripper. With the microgripper as the tool, it is possible to grasp objects of different materials with sizes between 100 and 500 μm and to release them. Some grasping actions were made on a 500 μm Teflon wire. The Teflon wire placed vertically could be gripped by the flat ends (Fig. 9(a)) or curved surfaces (Fig. 9(b)) of the microgripper.

Fig. 10 compares the tip displacements of the microgripper obtained from the FEA simulations and the experiments. Under ideal conditions, the displacements obtained from the FEA simulations were larger than those obtained from the experiments.

The relationships between applied voltages and the operational displacements of the PZT actuator were identified. The results obtained in Fig. 11 show the expected hysteresis effect, which is related to the material properties of the piezoelectric ceramic inside the actuator. The strokes of the open and close motions of the microgripper tips were observed and measured. The relationships between the applied voltage to the actuator and the tip displacement are also shown in Fig. 11.

By comparison of the results in Fig. 11, it was evaluated that the microgripper mechanism has a mean amplification of 3.0 calculated by the average value of three sets of test readings and an elastic stroke range of up to 170 μm. It was also observed that the two tips of the microgripper had slightly different displacements. This could be due to the imperfection of the prototype fabricated.

An example of manipulation was performed using the microgripper device. The assembly of miniaturized gear systems, typically with diameters below 2 mm, requires the use of special micro-gripping tools. The miniature gears are typically of some hundreds of microns in size. Tasks of pick and place of miniature watch gears were carried out. Fig. 12 shows images of the microgripper tips approaching the gear part and closing of the tips to grasp the gear. In order to visualize the grasping process, the direction of the mechanical contact between the miniature gear and the microgripper was perpendicular to the rotation axis of the gear. The grasping motion was controlled so as to avoid damaging the tiny teeth of the miniature gear.

6. Conclusion

Design, fabrication and tests of a monolithic compliant-flexure-based microgripper were performed. The microgripper prototype was manufactured using micro-wire electrode discharge machining. A displacement amplification of 3.0 and a maximum stroke of 170 μm were achieved. The use of piezoelectric actuation allowed fine positioning. Micromanipulation tests were conducted to confirm potential applications of the microgripper with piezoelectric actuation in handling micro-objects. Simulation and experimental results have proven the good performance of the microgripper. The microgripper may be scaled to very small dimensions.

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