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Design, simulation and testing of electrostatic SOI MUMPs based microgripper integrated with capacitive contact sensor

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ABSTRACT

In this paper a detailed modeling, simulations and testing of a novel electrostatically actuated microgripper integrated with capacitive contact sensor is presented. Microgripper is actuated with lateral comb drive system and transverse comb system is used to sense contact between micro-object and microgripper jaws. The design is optimized in standard SOI-MUMPs micromachining process using L-Edit of MEMS-Pro. Finite element analysis of microgripper is performed in COVENTOR-WARE which shows total displacement of 15.5 μm at the tip of jaws when voltage of 50 V_{dc} is applied at the actuator. Finite element analysis of sensor part is performed and results are compared with analytical model. Modal analysis is performed to investigate mode shapes and natural frequencies of the microgripper. Microgripper is tested experimentally and total displacement of 17 μm is achieved at the tip of microgripper. The slight difference between finite element analysis and experimental results is due to small variations in the material properties, deposited during the fabrication process. The change in capacitance of capacitive contact sensor is linearly calibrated with the change in the displacement. The sensitivity of contact sensor is 90 fF/μm. The total size of microgripper is 5.03 mm × 6.5 mm.

1. Introduction

Micromanipulation of microparts in microassembly, biological cells in microsurgery and microparticles in material science is of great interest for scientists and engineers. Which results in innovation of microtools such as MEMS based microgripper, is a typical MEMS device used to grip, hold and transport micro-objects from one place to the other.

Microgripper can be classified on the basis of the mechanisms employed for their actuation and sensing. These involve thermally actuated microgripper, piezoelectric microgripper and electromagnetic microgripper, having different force sensing mechanisms like piezoresistive, optical and capacitive force sensors. Out of these mechanisms electrostatically actuated microgripper is of great interest because of following reasons:

(1) Temperature independence.
(2) Relatively fast response.
(3) No hysteresis.
(4) Satisfactory amount of force generation.
(5) Negligible amount of current flow through out microgripper combs.

The first electrostatic microgripper was designed by Kim [1] in 1992, with dual jaws actuation. Another microgripper presented in [2] is designed on electrostatic actuation and operated at 80 V_{dc}, provides total displacement of 20 μm at the tip of jaws. The design in [3] operates at 85 V_{dc} produce displacement of 25 μm at the tip of microgripper.

Sensing the gripping force is required in most of the grasping application that makes it very important to integrate sensor with microgripper to avoid the application of excessive force on the grasped object. This sensing becomes critical when such microgrippers systems are used for the manipulation of biological cells. The manipulation as such delicate objects requires the microgripper actuator to seize the movement of microgripper as soon as the contact between the microgripper jaws and micro-organism is established. The problem with earlier developed microgrippers is the absence of such sensors as integral part of the microgrippers.

In recent years, microgrippers integrated with force sensor have been reported in [4,5], however these techniques require complex micromachining processes thus making high fabrication cost and long development time. Another type of microgripper integrated with capacitive force sensor is given in [6,7]. In this mechanism, the micro-object is pushed by one jaw over the other during

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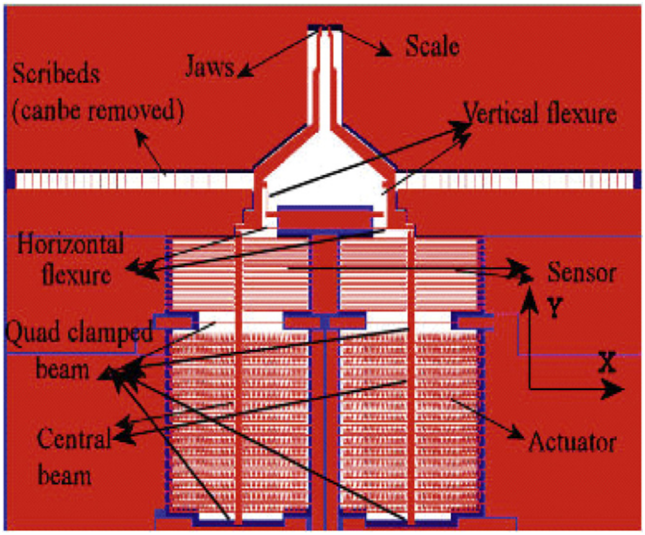

Fig. 1. Complete microgripper design with integrated capacitive contact sensor.

grasping process to activate the sensor, an operation not much desired to manipulate the micro-organisms. The displacement sensor reported in [10] is based on lateral change in the capacitance upon the application of force however it has not been integrated with microgripper.

In this paper, we report the design, simulation and testing of novel electrostatic microgripper with capacitive contact sensor for the manipulation of the biological objects. The sensor is used to sense the grasping of the object as soon as the contact is established between the jaws and the object to avoid the damage of the object due to excessive force. In the proposed design, both jaws are actuated using two sets of electrostatic actuators thus making the actuation voltage below 60 V_{dc}. The use of low actuation voltage makes the actuation circuitry simple that need to be integrated at later development stage to drive the actuator. The proposed design is implemented in commercially available standard micromachining process SOI-MUMPs. This reduces the prototyping cost and the development time while optimizing the design with known and tested design rules. Coupled electromechanical finite element analysis is carried out to check the behavior of the microgripper under different loading and boundary conditions. Micromanipulation testing of micro-object has been successfully performed using grasp-and-hold operations.

In this paper, Section 2 briefly explains the microgripper design. In Section 3 microgripper mathematical model is explained. Section 4 explains standard SOI-MUMPs micromachining process. In Section 5, we present finite element simulation of microgripper, while the experimental setup is described in Section 6. Finally experimental results are presented in Section 7, on the basis of these experimental results, the paper is concluded.

2. Microgripper design

Microgripper is actuated by simultaneously applying voltage at two sets of actuators connected to the gripper jaws through two central beams and two revolute joints as shown in Fig. 1. The actuator part is composed of comb drive system, in which one terminal of comb drive is fixed called stator. Other terminal is movable called rotor fingers. Due to the larger width and thickness of the central beam, the bending in this beam is considered negligible. Four sets of quad-clamped beams are attached to each central beam at two locations as shown in Fig. 1. These clamps ensure that the central beam motion is restricted in *x-axis*. Electrostatic force is generated

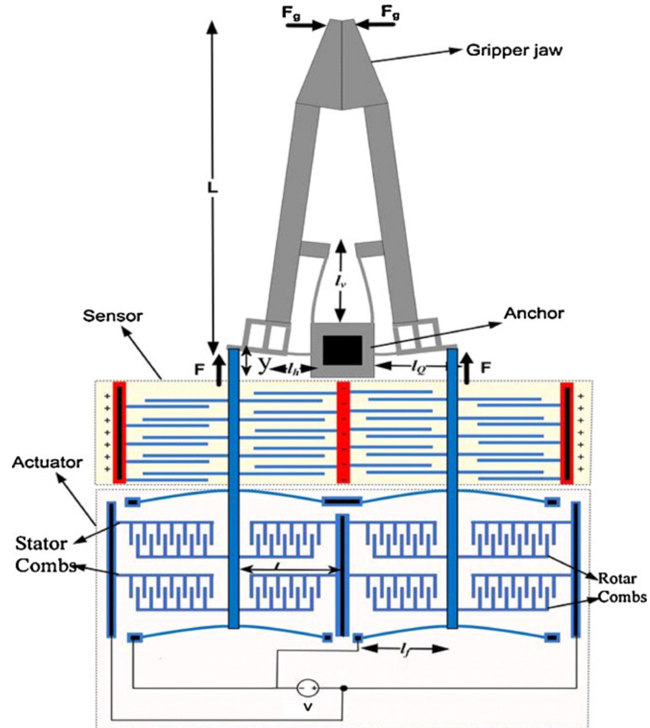

Fig. 2. Schematics of microgripper design.

in comb drive system due to which the central beam moves in *y-axis*. Each revolute joint consist of horizontal and vertical flexures to produce rotary motion in the two jaws towards each other. The revolute joint produces elastic restoring force to the jaws and ensures that the center of rotation of the jaws does not shift to make the firm grip of object. Upper part of the central beam is attached to a transverse comb differential capacitive contact sensor. When central beam moves under an applied voltage across the actuators combs, the motor fingers of the sensor moves to sense this motion. Thus overlap area of sensor fingers changes which results in capacitance change. This capacitance change can be measured by using a universal capacitance readout chip MS3110 [8] that provides an output voltage proportional to the capacitance change. When an object is grasped between the jaws under an applied electrostatic force, the jaws do not move further resulting in no capacitance change. This indicates to the controller (not shown here) that contact with micro-object has been established and the actuator voltage is not further increased.

3. Mathematical modeling of microgripper

3.1. Actuator

The electrostatic force required for actuation and equivalent stiffness of guided cantilever beam and quad clamped flexure beam system are calculated as:

$$F_{act} = \frac{N \cdot n}{2} \varepsilon \frac{(t \times l)}{d^2} \tag{1}$$

$$k = Et \left(\frac{4b_f^3}{l_f^3} + \frac{b_h^3}{4l_h^3} + \frac{b_v^3}{4l_v^3} \right) \tag{2}$$

Here N is total number of combs, n is the total number of fingers in each comb, ε is permitivity of free space, t is the thickness and l is the length of each comb in actuator as shown in Fig. 2, d is the gap between fingers and E is Young's Modulus of material. The