13th National Conference on Mechanisms and Machines (NaCoMM07),
IISc, Bangalore, India, December 12-13, 2007

NaCoMM-2007-112

Optimizing Design of Piezoelectric Actuated Compliant Microgripper Mechanism

Pretty Khare, G. B. Madhab*, C. S. Kumar, and P. K. Mishra
Department of Mechanical Engineering, Indian Institute of Technology Kharagpur-721302, India

* Corresponding author (email: madhab@mech.iitkgp.ernet.in)

Abstract

Compliant mechanisms have advantages of having no assembly joints and ease-of-manufacture. Optimal motion and force response of the mechanism depends on various parameters of the compliant mechanism and the actuation scheme used. This paper describes the design of a two-fingered bio-inspired micro-gripper actuated by a pair of agonist-antagonist piezoelectric actuators. Coupled-field finite element analysis is carried out to optimize the design of a microgripper and its dimensions for maximum displacement gain and to obtain a relationship between the input voltage and output tip displacement. The design is optimized with respect to the hinge radius, position of the hinge, length of links, material concentration etc. Also volumes having almost zero stress concentrations can be removed to decrease the mass of the gripper. The paper describes a systematic study on the variations in design for good performance of the mechanism in terms of large displacements and improvements for areas of high stress, low strain etc. were suggested.

Keywords: Design optimization, Micromanipulation, Compliant mechanisms

1 Introduction

A compliant mechanism can be defined as that a structure utilizes its elastic characteristic to generate a specifying mobility on the predetermined portion [6]. Different from the recognized rigid-linkage, the compliant mechanism has joint-like structure instead of the conventional joints to perform the relative motion of force and movement transmission. Such a flexure-generated mechanism can be broadly useful in engineering for overcoming the existing un-solving problems of stress concentration and structural fatigue. Particularly, in the current micro-age, the advantages of a compliant mechanism including the single formation, fewer assembly parts, manufacturing cost deduction and friction deduction between the contacts. Compliant mechanisms have already been used in many applications including product design, MEMS, adaptive structures, surgical tools, micro-grip and the micro-stage [2,3,4,7].

Generally, there are two approaches for the design of compliant mechanism, one is the kinematic synthesis approach based on the traditional rigid-body kinematics, and the other refers to the continuum synthesis approach based on the topology optimization method of continuum structures. The former approach is the so called the design approach of pseudo-rigid-body mechanism [6], where the design is firstly performed by synthesizing a rigid-body mechanism, and then the flexibility is introduced to redesign the hinged joints of rigid-body parts as flexibility hinges in such a way the performance of the resulting compliant mechanism is roughly functions like a pseudo-rigid-body mechanism when compared to that of a rigid-body mechanism. Methods based on this approach are limited to fixed topology and lumped compliance, so the design approach is classified as lumped compliant mechanisms. A lumped compliant mechanism can only bend in flexural hinges, and so that the material around the hinge is usually overstressed and overstrained. The latter approach, based on topological optimization methods [1], allows the change of topology, and the movement of the mechanism is obtained via the distributed elastic deformation of the whole mechanism and the resulting mechanism is not subject to overstress or overstrains in contrast to that of a lumped compliant mechanism. Thus the latter design approaches using topology optimization are named distributed compliant mechanism designs.

Piezoceramic stack actuators are often used in conjunction with flexible coupling structures like compliant mechanisms to amplify their stroke while providing useable force output [9]. Most of the micro-grippers developed in recent years still lack of the systematic mechanism design background in the overall design scope of microgripper [5]. The main objective of this investigation is to analyze and optimize a coupled piezoactuated and compliant micro-gripper for gripping and manipulation. An effort has been made to optimize the design of the micro-gripper for the displacement of the gripper arm and the stress on the hinges. A parametric study has been done by varying the amount of material removed from the gripper arm. Effect of changing three parameters has been studied: thickness of material left in the gripper arm, number of structural elements in the arms of the microgripper. Also the effect of adding a truss in the gripper arm has been studied for varying thickness of the truss links.

2 Concept Design and Simulation

Based on the crab's claw mechanism [8], initially a simplified kinematic linkage model was developed as shown in Fig. 1. The simple mechanism studied in this paper has the advantage of manipulating the objects in addition to the gripping. The agnostic and antagonistic mechanisms required for the closure muscle and the opener muscle are assumed to be a pair of linear piezoelectric stack actuators which are an available technology and can be used in the design with electronic control in a small space. A corresponding CAD model of a proposed microgripper is developed as shown in Fig. 2. Provisions are made in the gripper structure such that four piezoelectric actuators can be attached and actuated simultaneously.

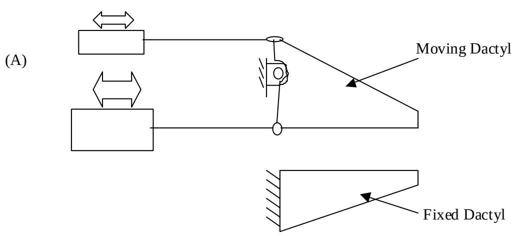

Figure 1: Kinematic model of a crab's claw [8].

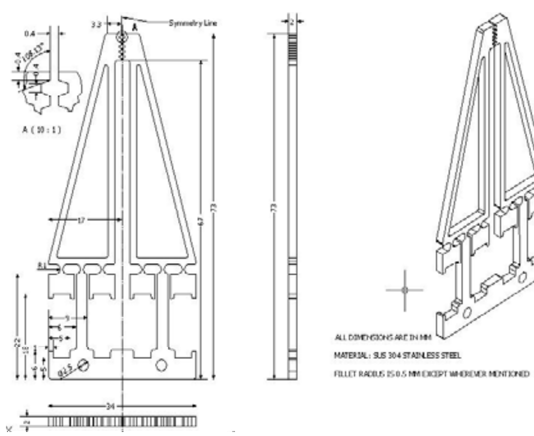

Figure 2: CAD model of a dual actuated microgripper with two independent gripper arms.

The gripper mechanism motion is then simulated by coupling structural and electrical fields using the finite element software ANSYS.

A piezoelectric model requires permittivity (or dielectric constants), the piezoelectric matrix, and the elastic coefficient matrix to be specified as material properties. In this work, the piezoelectric actuator used is a low voltage PZT with displacement of 10 microns and is modeled in using a 3-D coupled field solid element SOLID5 that has eight nodes with up to six degrees of freedom at each node.

The material properties and specifications of piezoelectric material are shown in Table 1.

Table 1: Parameters of Piezoelectric actuator material

PZT Specification	*Value*
s_{11}	$16.5e^{-12}\ m^2/N$
s_{12}	$-4.78e^{-12}\ m^2/N$
s_{13}	$-8.45e^{-12}\ m^2/N$
s_{33}	$20.7e^{-12}\ m^2/N$
s_{44}	$43.5e^{-12}\ m^2/N$
s_{66}	$40.56e^{-12}\ m^2/N$
d_{15}	$7.41e^{-10}\ C/N$
d_{31}	$-2.74e^{-10}\ C/N$
d_{33}	$5.93e^{-10}\ C/N$
K_{11}	3130
K_{33}	3400
ρ	$7500\ kg/m^3$
ν	0.3

Where, $s^E\left(m^2/N\right)$ are the piezoelectric elastic compliance coefficients, $d\left(C/N\right)$ are the piezoelectric strain coefficients, and K are the piezoelectric relative permittivities for the piezoelectric actuator [10].

The tensor matrices for the piezo actuator can be represented as follows:

$$\text{Relative permittivity matrix} = \begin{bmatrix} K_{11} & 0 & 0 \\ 0 & K_{11} & 0 \\ 0 & 0 & K_{33} \end{bmatrix} \qquad (1)$$

Piezoelectric elastic compliance matrix

$$\left(S^E\right) = \begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{11} & s_{13} & 0 & 0 & 0 \\ s_{13} & s_{13} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}-s_{12}) \end{bmatrix} \qquad (2)$$

Piezoelectric strain coefficient

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \qquad (3)$$

Based on the parameters of a general stacked piezoelectric actuator that can be procured off-the shelf in market, finite element coupled-field analysis was carried out to predict the output displacement of microgripper tip displacement for a given input voltage. The piezo actuator shows the hysteresis effect as shown in Fig. 3 which is its inherent material property. With this approach the combined simulation and response of the piezo actuator and micro-gripper together are analysed. This will not only complete the design but also allow easier identification of parameters for a control design.

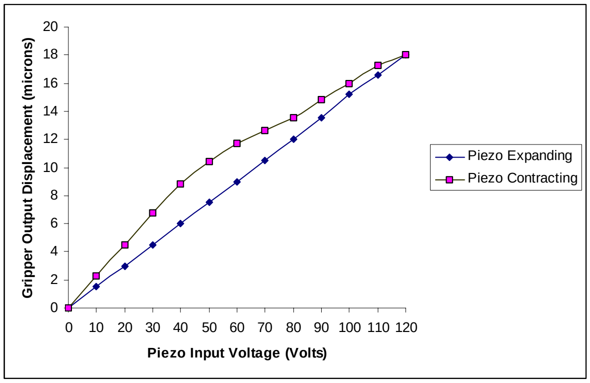

Figure 3: Displacement characteristics of piezo actuator for given input voltage.

3 Design Optimization

The design of double actuated gripper proposed has to be optimized with respect to the hinge radius, position of the hinge, length of various links, material concentration etc. Also volumes having almost zero stress concentration can be removed to decrease the mass of the gripper. Results of FEM analysis of various designs are given in a tabulated form in Table 2 and Table 3.
Material properties assumed for the analysis are: Young's modulus = 205 MPa, Poisson's ratio = 0.4, input displacement = 10 microns for all the cases.

Table 2: Variation of max. displacement and maximum stress with variation in the amount of material removed from the gripper arm

Design No.	*Amount of material left in the gripper arm (in mm)*	*No. of equally spaced links added to the gripper arm*	*Link thickness added to the gripper arm (in mm)*	*Max. disp. of gripper arm (in microns)*	*Max. Stress (N/m2)*
1	N.A.	N.A.	N.A.	17.5	17.8
2	1	N.A.	N.A	19.1	19.3
3	2	N.A.	N.A.	16.6	16.6
6	1	1	1	17.8	18.0
7	1	1	2	17.6	17.8
9	1	2	1	17.7	18.6
11	1	2	3	18.6	18.2
13	1	3	2	18.9	19.1
14	1	3	3	19.1	18.9
17	2	1	3	18.7	19.3
18	2	2	1	17.1	16.9
19	2	3	1	19.2	19.8
21	3	1	1	17.2	18.0
22	3	1	2	17.3	17.5
23	3	1	3	17.2	17.9
26	4	1	1	17.3	18.1
27	4	1	2	17.4	18.7

Table 3: Variation of max. displacement and max. stress with variation in the thickness of truss

Design No.	*Amount of material left in the gripper arm (in mm)*	*No. of equally spaced links added to the gripper arm*	*Thickness of each link added to the gripper arm (in mm)*	*Max. disp. of gripper arm (in microns)*	*Maximum Stress (N/m2)*
1	1	1	16.9	17.17	1
2	1	2	18.6	20.23	1
3	2	1	18.5	19.48	2
4	3	1	19	19.35	3

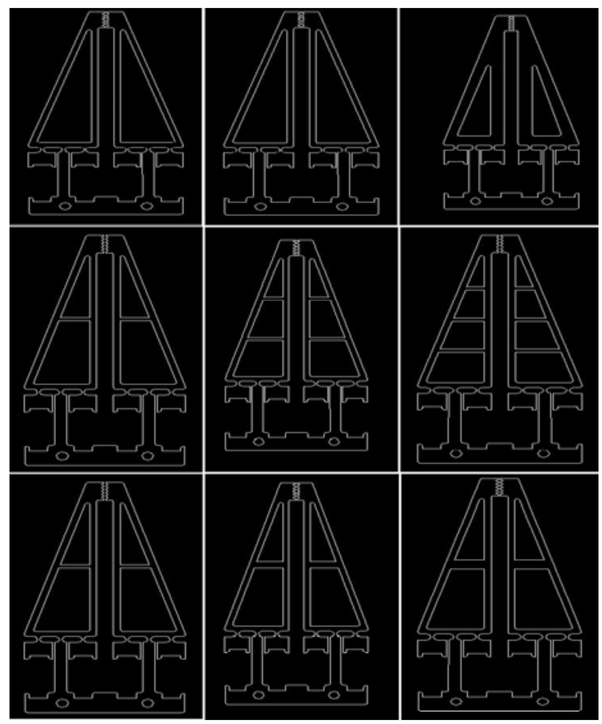

Figure 4: Top figures show the thickness variation, Middle figures show the addition of bars and bottom figures show the variation of bar thickness.

4 Results and Discussions

The initial proposed design of the double actuated micro-gripper is not the optimal design. The aim of this FEM analysis was to find out a model, which has maximum gain (output/input). Keeping the input same for all the designs, more the output, more is the gain. From the table it is clear that gain can be increased by removing the material from places of zero stress concentration, increasing the width of the micro-gripper, increasing the thickness of the hinge and by increasing the width of the bar. Although by varying these parameters the stress concentration in the flexure hinge increases but it is within the safety limits. Thus an optimal design (having maximum gain) can be synthesized by superimposing these individual changes.

It is observed that maximum displacement of the gripper arm is more or less proportional to the maximum stress concentration in the hinges i.e. as the maximum displacement increases the stress concentration also increases. As the thickness of the material left in the bar increases (shown in Fig.4 top three configurations), the maximum displacement of the gripper arms and the maximum stress concentration decrease initially but start increasing when the material thickness is between 3m to 4mm. Similar trends can be found in the number of links added to the gripper arm as shown in Fig. 5. Initially the displacement and the stress decrease with the increase in the number of links but after the number of links is 3, these parameters start increasing. But varying the thickness of the link does not have much effect on the displacement of the gripper arm but reduces the stress concentration in the hinges. Also, introduction of a truss in the gripper arm leads to an increase in the displacement, but the stress concentration increases more than the increase in the displacement. More the thickness of the truss link, higher is the stress concentration in the hinges. Based on the observations, the design in which the thickness of material left in the gripper arm is 1mm, along with 2 links of 3mm each looks to be the most optimum design as the increase in the stress concentration is overshadowed by the increase in the arm displacement.

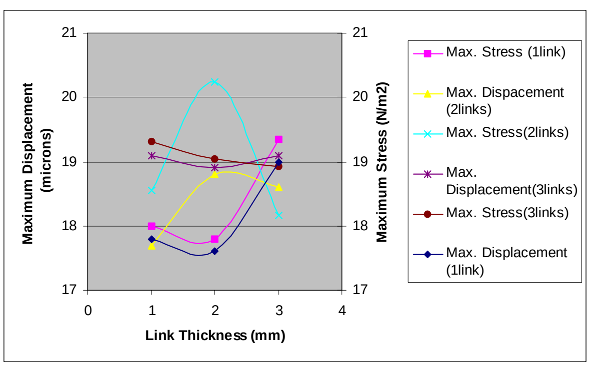

Figure 5: Displacement and stress variations with different parameters.

5 Conclusions

In this paper some aspects of the design of compliant micro grippers has been addressed. These grippers actuated by linear piezoelectric devices need to be well optimized for best performance in terms of displacement and force capabilities while retaining a good life time operation without running through high stress concentrations at the weak points in the mechanism. The paper shows a combined model of piezoelectric actuator and mechanism considered through a coupled field analysis approach, a procedure adopted from the finite element based methodology of materials analysis. This has further been extended to consider the optimization of the mechanism using design optimization approach for optimal displacement and stress concentration in the system. Results are provided for a biologically inspired dual actuator per finger microgripper considered in this work.

References

[1] Ananthasuresh, G. K., and Kota, S., "Designing compliant mechanisms," ASME Mechanical Engineering, November 1995, pp. 93-96.

[2] Ando Y., Sawada H., Okazaki Y., Ishikawa Y., Kitahara T., Tatsue Y. and Furuta K., (1992), "Development of Micro Grippers", Journal of Robotics and Mechatronics, Vol.2, pp. 214-217.

[3] S. Ballandras, S. Basrour, L. Robert, S. Megtert, P. Blind, M. Rouillay, P. Bernede, and W. Daniau, "Micrograppers fabricated by the LIGA technique," *Sensors and Actuators A*, Vol.58, 1997, pp. 265-272.

[4] Carrozza, M. C., Eisinberg A., Menciassi A., Campolo D., Micera S. and Dario P., (2000), "Towards a Force-Controlled Microgripper for Assembling Biomedical Microdevices", Journal of Micromechanics and Microengineering, Vol.10, pp. 271-276.

[5] Chang R. J., Wang H. S. and Wang Y. L., (2003), "Development of Mesoscopic Polymer Gripper Systems Guided by Precision Design Axioms", Precision Engineering, Vol. 27, pp. 362-369.

[6] Howell, L. L., Compliant Mechanisms, John Wiley & Sons, 2001.

[7] Keoschkerjan R. and Wurmus H., (2002), "A Novel Microgripper With Parallel Movement of Gripping Arms", 8th International Conference on New Actuators, Actuator 2002, Bremen, Germany, June 10-12, pp. 321-324.

[8] Madhab G. B., Kumar C. S. and Mishra P. K., (2005), "Design of a Bio-inspired Piezoelectric Compliant Miniature Gripper", Proceedings of ISSS 2005 International Conference on Smart Materials Structures and Systems, July 28-30, 2005, Bangalore, India, pp. SD-17-24.

[9] Yu J., Bi S., Zong G. and Liu X. J., (2003), "On the Design of Compliant-based Micro-Motion Manipulators with a Nanometer Range Resolution", Proceedings of the 2003 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM 2003, July 20-24, Vol. 1, pp. 149-154.

[10] Goldfarb M. and Celanovic N., (1997), "Modeling Piezoelectric Stack Actuators for Control of Micromanipulation", IEEE Control Systems Magazine, Vol. 17, No. 3, pp. 69-79.