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Displacement Analysis and Output Force Estimation of A Compliant Robotic Microgripper

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ABSTRACT

Micromanipulators should be able to accurately control gripping force in order to avoid any damage to the small size delicate objects, which are less than 1mm size. Hence gripping force determination according to application and subsequently control of gripping is an essential parameter in micromanipulators. The present work deals with the study of a Four-piezo actuated compliant micro gripper, kinematical modelling of the micro gripper and estimation of output force using Pseudo-rigid body model (PRBM) of the gripper. The study involves computation of tip displacement of the micro-gripper using the available mathematical equations and formulae and thereafter comparing the results with Finite Element Method values of the 3D model of the gripper using ABAQUS. The current research also involves calculation of the gripping force using equations of motion of one finger of the gripper using SIMMECHANICS. Finally the feedback control mechanism is developed using SIMULINK to control the gripping force.

Keywords: Compliant Mechanism, PRBM (Pseudo-rigid body model), Abaqus, Simmechanics, Simulink.

I. INTRODUCTION

Throughout the development of the Micro electromechanical systems (MEMS) field, there has been an increasing interest in developing a system that would allow the manipulations of small structures in the µm range, namely micro grippers. Micro gripper is one of the key elements in micro robotics and micro assembly technologies for handling and manipulating micro objects such as micro mechanical parts, electrical components, biological cells, micro materials etc.

Conventional mechanisms built with revolute joints and transmission based mechanisms are not suitable to cater to the requirements of precision handling as they cannot precisely control their motion and the gripping force due to the presence of backlash and coulomb friction in their joints. So to those, mechanisms move only by the deformations using flexural hinges instead of conventional joints and bearings etc. are used. With a “no-assembly” gripper design, many critical specifications such as linear displacement, micro accuracy, zero backlashes, no friction, and no wear can be addressed through exploitation of compliant mechanism design [1].

Byoung Hun Kang and John T. Wen [2] developed design by considering the pseudo rigid body model as an approximate description of mechanism. Mohd. Nashrul et.al [3] mentioned that different objects require different gripping behaviour to achieve high accuracy handling performance. J.H. Kyung et.al [4] designed microgripper contains two different flexible hinges by making the flexible hinge near to the tip of the gripper thinner in order to concentrate most of the gripping force. Mahmoud Helal et.al [5] presented the design of compliant grip and move manipulators with parallel movement tips.

II. METHODOLOGY AND GEOMETRIC MODELLING

A. Kinematic Synthesis and Concept Design

A Study of arthropod’s grasping mechanisms (specifically crustaceans like crabs, lobsters etc.) was carried out from available literature. Then a crab’s claw mechanism is selected for further kinematic study based on the design requirement/criteria.

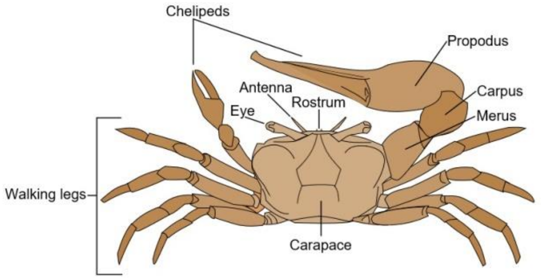


Figure 1. Crab detail parts.

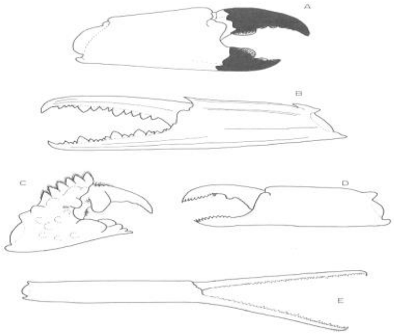


Figure 2. Claw structure for various crab species.

B. Kinematic Linkage Model for the Crab's Claw

Based on the crab's claw mechanism, a kinematic linkage model was developed as shown in Fig.3. The closer muscle is assumed to be a bigger linear actuator having large actuation force and the opener muscle is assumed to be a smaller linear actuator having small actuation force.

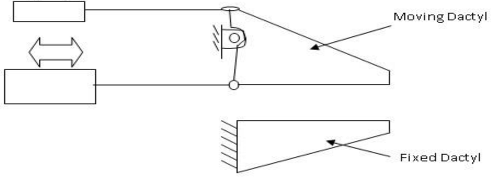


Figure 3. Kinematic model of a crab's claw

C. Design of a Miniature Gripper with Two Piezo Actuators

A pseudo-rigid-body-model (PRBM) for the mechanism is developed for closing. It is assumed that while one actuator is active, other one is idle and have very high stiffness. If only the bending (rotational) stiffness of flexure hinges is considered in modeling the static behavior of the microgripper, it will have less motion range than the theoretical range. Therefore to improve the PRBM model the flexure hinge stretching has been incorporated [6]. The loss of motion due to coupling between the piezo actuator and the microgripper mechanism is neglected. Fig.5 shows the initial CAD model of the micro-gripper.

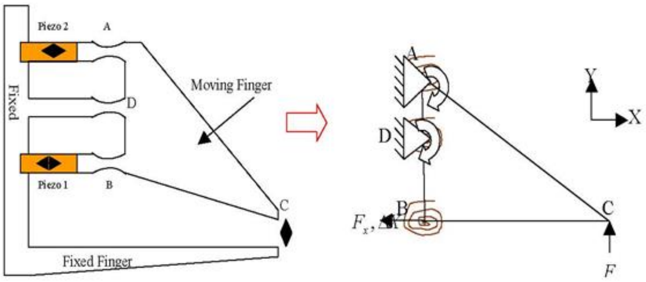


Figure 4. Flexure-based Microgripper Mechanism and its PRBM.

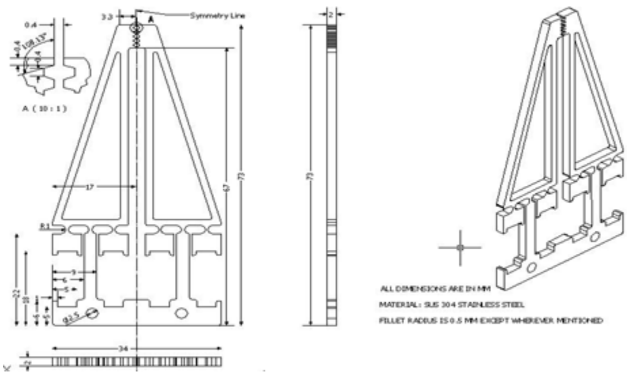


Figure 5. AutoCAD drawing of dual actuated micro-gripper

III. Microgripper Kinematics

A. Pseudo-rigid-body-model (PRBM) (for Four-piezo actuator mechanism)

The flexure-based mechanism analytically studied using PRBM or lumped parameter system for analysing compliant mechanisms. The model was derived from the flexure-based mechanism by replacing flexure hinges with rotational springs with certain spring stiffness constant calculated from the model [7]. Since the mechanism is symmetric, only half portion is analysed.

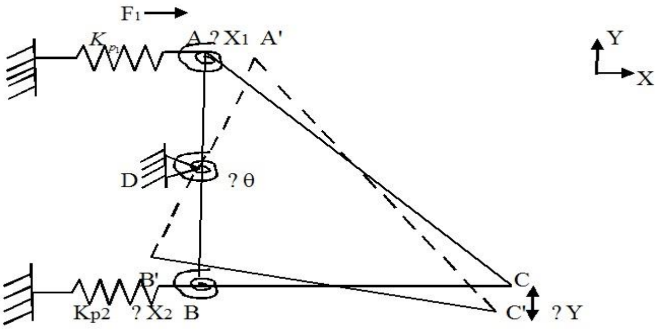
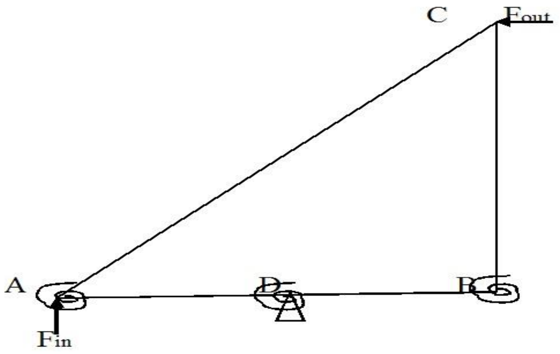


Figure 6. PRBM of the microgripper.

The output displacement of the gripper can be written as,

$$\Delta Y = \frac{3 \times F_1 \times BC \times AD \times r^{0.5} \times \Pi}{3\Pi r^{0.5}\left(K_{p1} \times AD^2 + K_{p2} \times BD^2\right) + Ebt^{2.5}}$$

B. Estimation of the gripping force



$$F_{out} = \frac{\left(F_{in} \times AD - \left(\frac{3}{2} \times K_\theta \times \frac{\Delta Y}{BC}\right)\right)}{BC}$$

Figure 7. Gripping Force

C. Finite element analysis of microgripper (Four piezo actuated mechanism)

The model is designed in CATIA V5R19 and later imported in ABAQUS and is meshed with "20-node Quadratic brick element" because of its accuracy. The ABAQUS software is used to predict the output displacement and the Fig.9 shows the displacement distribution along the mechanism while closing. The maximum displacement is observed at the microgripper tip region which fulfils the desired requirement for gripping.

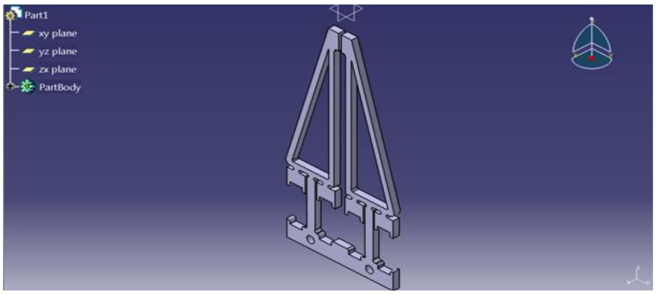


Figure 8. 3D model of the four piezo actuated microgripper using CATIA V5R19.

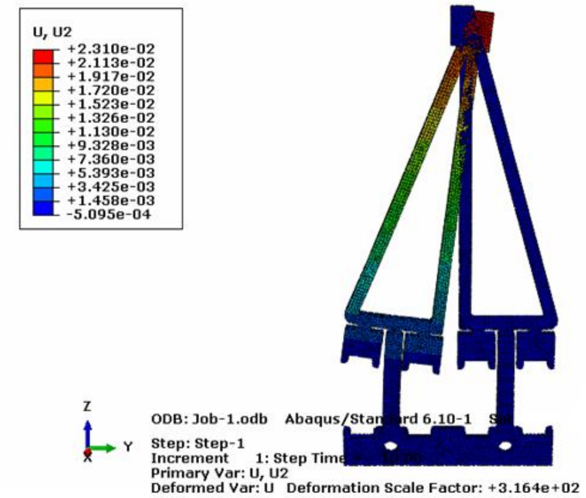


Figure 9. Displacement distribution of microgripper.

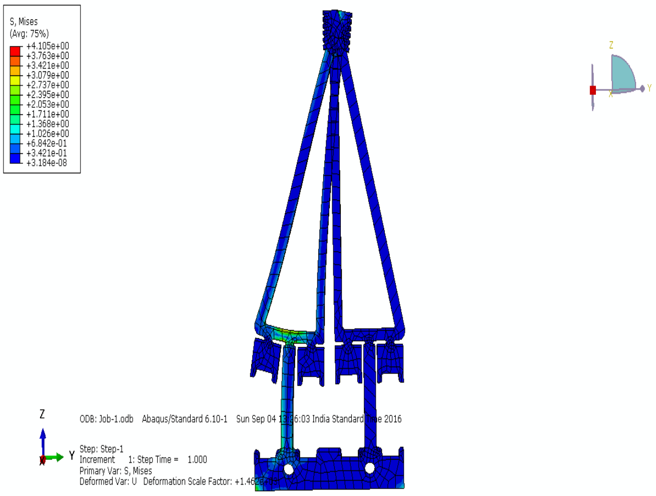


Figure 10. Maximum stress is observed at the minimum thickness of the flexural hinge.

D. Comparison of results

Finally the output displacement obtained by PRBM are compared with ABAQUS results as shown in table 1 and plotted graphs as shown in Fig. 11 and 12.

Table 1. Comparison between ABAQUS and PRBM results for the same input displacements

Input displacement (µm)	ΔY (PRBM) (µm)	ΔY (ABAQUS) (µm)	Gain $(\frac{\Delta Y}{\Delta X})$ (PRBM)	Gain $(\frac{\Delta Y}{\Delta X})$ (ABAQUS)	% Error (PRBM)
5	23.053	23.100	4.610	4.620	0.20
10	46.102	46.220	4.610	4.622	0.25
15	69.153	69.380	4.610	4.625	0.32
20	92.204	92.602	4.610	4.630	0.43

25	15.255	115.830	4.610	4.633	0.49
30	38.306	139.106	4.610	4.636	0.57
35	61.357	162.407	4.610	4.640	0.65
40	84.408	185.788	4.610	4.644	0.74
45	07.460	209.160	4.610	4.648	0.81
50	230.511	232.510	4.610	4.650	0.86

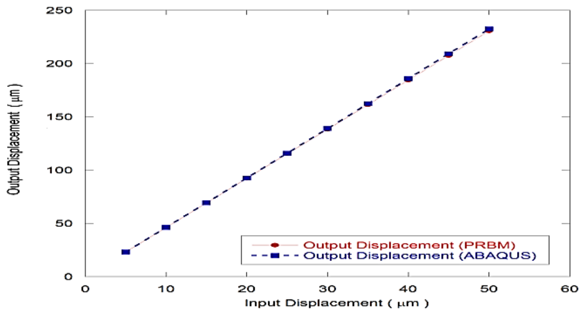


Figure 11. Comparison of PRBM and ABAQUS results.

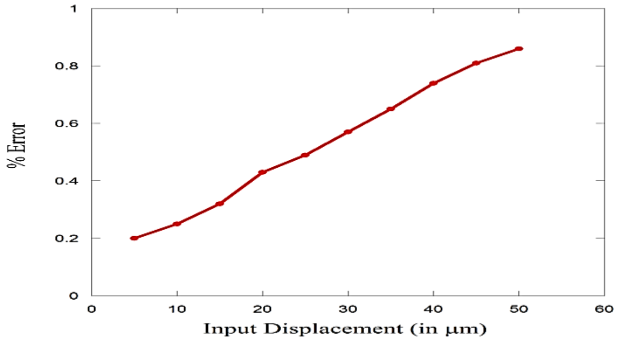


Figure 12. % Error PRBM for given input displacements.

IV. Equation of motion and control of the microgripper.

In this section two cases are considered. Because the model is symmetrical one finger of the model is modelled since it can be extended to two. In the first case the finger without the object grasping is studied and in the second one the finger when grasping an object is studied. The assumptions made for deriving the model are: The fingers are rigid and do not have any structural compliance. If any compliance is found it is to be taken as lumped parameter in the hinges or in the gripper object.

Case (1): When no object is present:

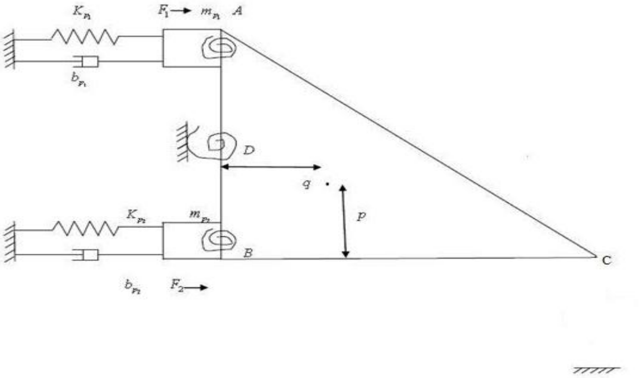


Figure 13. Dynamic model of the microgripper when no object is present.

The equation of motion can be derived using Euler-lagrangian equation,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right)-\frac{\partial L}{\partial \theta_i}+\frac{\partial R}{\partial \dot{\theta}_i}=\tau_i, i=1,2,3,4,.....n$$

The equation of motion is written as,

$$\left[M\left(p^2+q^2\right)+I+m_{p1}AD^2+m_{p2}BD^2\right]\ddot{\theta}+\left(b_{p1}AD^2+b_{p2}BD^2\right)\dot{\theta}$$
$$+\left(K_{\theta,A}+K_{\theta,D}+K_{\theta,B}+K_{p1}AD^2+K_{p2}BD^2\right)\theta=\left(F_1\times AD-F_2\times BD\right)$$

Case (2): When object is present:

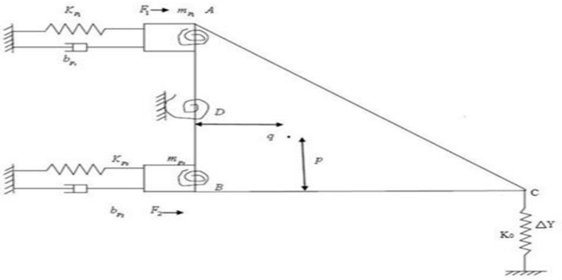


Figure 14. Dynamic model of the gripper when object is present

The equation of motion can be written as,

$$\left[M\left(p^2+q^2\right)+I+m_{p1}AD^2+m_{p2}BD^2\right]\ddot{\theta}+\left(b_{p1}AD^2+b_{p2}BD^2+b_0BC^2\right)\dot{\theta}$$
$$+\left[K_{\theta,A}+K_{\theta,D}+K_{\theta,B}+K_{p1}AD^2+K_{p2}BD^2+K_0BC^2\right]\theta=\left(F_1\times AD-F_2\times BD\right)$$

A. Simulation

A part from Analytical approach used to model the system, a simulation model has also been established to study the characteristics of the microgripper.

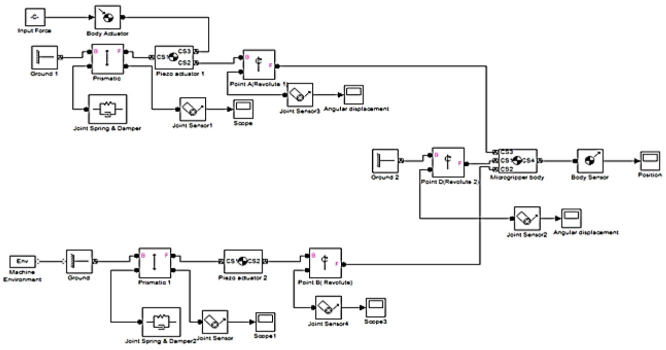


Figure 15. SIMMECHANICS model for simulation of gripper dynamics when no object is present

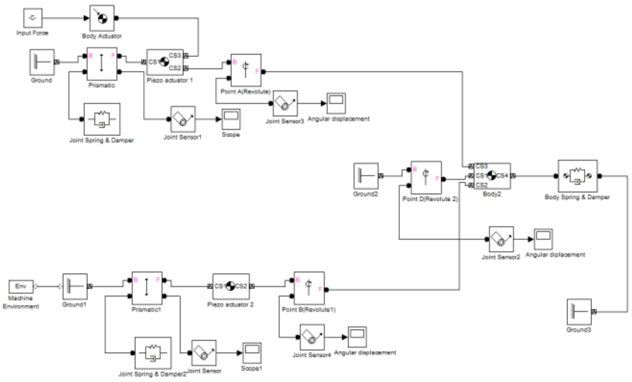


Figure 16. SIMMECHANICS model when translational spring between the tip of the microgripper and ground is present.

Table 2. Angular displacements and gripping force with change in time

Time (sec)	Angular displacement(θ) (rad)	Displacement (ΔY) (mm)	Gripping force (F_{grip})(N) (ForK_0=50×10^3 N/m)
5	0.00145	0.06438	3.21
6	0.00105	0.04662	2.33
7	0.00132	0.0590	2.95
8	0.00172	0.0767	3.83
9	0.00148	0.06572	3.28
10	0.00138	0.0612	3.06

From Table 2 the average gripping force is 3.732 N. For controlling of this gripping force the mathematical model is used and a PID force controller is developed in SIMULINK.

B. PID Controller

A proportional-integral-derivative (PID controller) is a generic control loop Feedback mechanism (controller) widely used in industrial control systems. A PID controller is the most commonly used feedback controller.

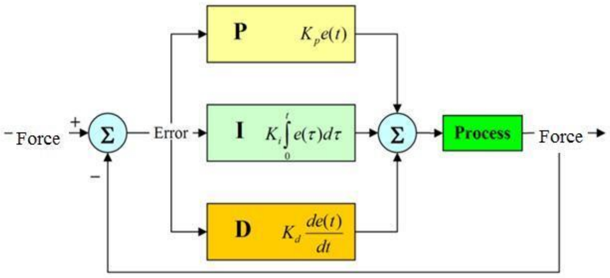


Figure 17. A PID force controller in a closed loop system.

Tuning of a controller loop is the adjustment of its control parameters to optimum values for the desired control response [8]. The original method of tuning PID controllers was suggested by John G. Ziegler and Nathaniel B. Nichols in 1942.In order to have a precise gripping a good force controller is needed. With the help of SIMULINK model, a PID controller developed and its performance tested.

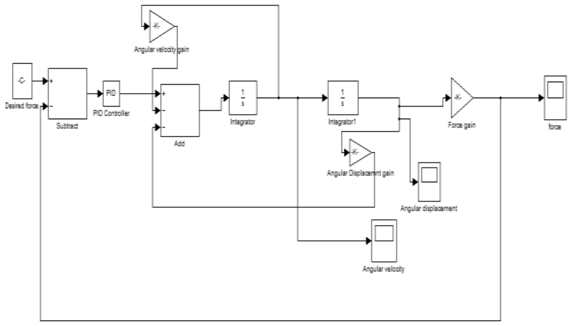


Figure 18. PID force controller for microgripper.

V. CONCLUSION

- A four-piezo actuated microgripper is studied and the PRBM of the microgripper is validated to be the approximate model for the microgripper through the FEA simulations of the 3D model using ABAQUS.
- As the trails to obtain controlled simulation using ABAQUS were not contributed to the progress of the solution for the problem, we opted for SIMMECHANICS.
- The equation of motion of the gripper is derived and the microgripper is modeled in SIMMECHANICS and the gripping force has been found out as the combination of deflection of the spring and stiffness of spring. SIMMECHANICS provides direct reaction forces in case of joints and constraint drives only.

- Finding the contact force between the object and microgripper directly using SIMMECHANICS is not possible. So, we used an indirect approach to find out the gripping force by modeling a linear translational spring in between the body and ground which can generate the force based on the relative displacement between two bodies. Hence by measuring the change in angle we calculated the deflection of the spring and thus gripping force. But this case is limited to the objects which are of known stiffness.
- The force is controlled using PID force controller modeled in SIMULINK and the control behavior with respect to the stiffness of the object is verified.

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