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Design Optimization of a Flexible Hinge Compliant Micro-Gripper Mechanism with Parallel Movement Arms Using Pseudo-Rigid-Body Model

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Abstract: Nano/Micro-electro-mechanical-system (NEMS/MEMS) consists of couplings of electrical and mechanical components within the micro-scale. Their nonlinear working state makes their analysis complex and complicated. Compliant mechanisms can (CMs) achieve a specified motion as a mechanism without relying on the use of joints and pins. They have broad application in precision mechanical devices and Nano/Micro-electro-mechanical-systems. Compliant mechanisms are suggested as alternates for simplification of assembly and for miniaturization. The design synthesis of compliant mechanisms yields optimized topologies that combine several stiff parts with highly elastic flexural hinges. In this paper, Finite Element Analysis (FEA) analysis and design of a compliant micro-gripper compliant mechanism with parallel movement arm are presented by employing its Pseudo Rigid Body Model (PRBM), which leads to the establishment of high performance mechanism. This micro-gripper is capable of delivering high precision and fidelity manipulation of micro objects. The mechanism adopts a flexure-based concept on its joints to address the inherent nonlinearities associated with the application of conventional rigid hinges.

Keywords: NEMS/MEMS, Compliant mechanism, Micro-gripper, Multi-objective function, pseudo-rigid-body model (PRBM)

Introduction

Micro-electro-mechanical-systems (MEMS) are an electromechanical integrated system where the feature size of components and the actuating range are within the micro-scale. Unlike traditional mechanical processing, manufacturing of MEMS device uses the semiconductor production process, which can be compatible with an integrated circuit, and includes surface micromachining and bulk micromachining. Due to the increasingly mature process technology, numerous sophisticated micro structural and functional modules are currently available. Therefore, greater optimized performance of the devices has been developed. On the MEMS functionality, MEMS can be broadly divided into two categories called micro-sensors in order to detect the information or called micro-actuators which act corresponding to detected information. Electrostatic-driven MEMS devices have advantages of rapid response, lower power consumption, and integrated circuit standard process

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[§] Egyptian Armed Forces, Egypt; saidhabib2000@hotmai.com compatibility. Among the present MEMS devices, many are electrostatic-driven MEMS devices, such as capacitive pressure sensors, comb drivers, micro-pumps, inkjet printer head, RF switches, and vacuum resonators [1-6].

A mechanism is a device that transfers or transforms motion, force, or energy in order to perform work. Traditional rigid-body mechanisms contain moving parts and joints, such as gears and pins, which work together in order to carry out the function of the mechanism. Compliant mechanisms, on the other hand, work by flexing all or some of their parts. Compliant mechanisms are flexible mechanisms that transfer an input force or displacement to another point through elastic body deformation. These are usually monolithic (single-piece) or joint-less structures with certain advantages over the rigid-body, or jointed, mechanisms. A few examples that come to mind are a spring, tweezers, and a bow-and-arrow. Many devices, such as a stapler, are a combination of rigid-body and compliant mechanisms [7, 8].

One of the advantages of compliant mechanisms is their ability to be miniaturized. They can be injection-molded out of one piece of material, or manufactured in the same manner as integrated circuits. This makes them ideal candidates for use in micro-electro-mechanical systems (MEMS). Compliant mechanisms are more difficult to design well than their rigid-body counterparts. Predicting their actions and the effect of stress and fatigue over their lifespan requires an iterative design process. This process can be lengthy, particularly for inexperienced designers who lack a “big-picture” view of what goes into good design and why [9-12].

Compliant mechanisms have been investigated by many researchers because they are less expensive, lighter, and easier to manufacture when compared to rigid-link mechanisms [7, 8]. Especially in recent years, the interest in the field of compliant mechanisms has grown steadily [13-15]. One disadvantage of compliant mechanisms is the complexity of their analysis and design. In order to simplify their analysis, the pseudo-rigid-body model technique (PRBM) has been frequently used in the literature [7, 8]. If the number of small-flexural pivots of a compliant mechanism is increased so that the degree-of-freedom is more than one, the design of the resulting mechanism becomes quite challenging.

Flexure hinges are commonly utilized in compliant mechanisms for the applications in micro/nano-instruments, machines and systems such as scanning tunnel microscope, X-ray lithography, mask alignment, and micro-manufacture [16–18], where high positioning accuracy and resolution are the necessary and crucial requirements to fulfill the tasks. Flexure-based mechanisms can overcome the shortcomings such as stiction, friction, and backlash, existing in conventional precision systems with sliding and rolling bearings, and implement positioning with the capability of smooth motion, free of friction and lubrication [19, 20]. The positioning accuracy of flexure-based mechanisms can be further improved by utilizing laser-interferometer-based sensing technique for independent position and displacement measurement and tracking [21].

The most micro-assembly processes at present rely on human dexterity which is technically ineffective in term of moving towards mass production. Micro-assembly must have the capacity to address the complexity of assembling micro devices while maintaining low cost attributes and high yield to reach the consumer. Activities that require this technology encompasses certain assembly and parts maneuvering operation for insertion, bonding, mounting, transportation, and sealing procedures. Three major areas of study have been classified as the main focus in micro-assembly technological development and currently receive large attention by micro-system researchers in academia. The development of ultra-precision positioning stage, nano-measurement technology and grasping methodologies [22, 23] constitute a major set of elements under extensive research to achieve successful micro-assembly operations. In addition, the rapidly growing exploration in haptics and virtual reality technologies will enable further advancement towards human perception within the micro world to attain dexterous manipulation between the robot and micro objects [24, 25].

Furthermore, the application of novel measurement techniques and methodologies via the utilization of high precision magnification devices such as scanning electron microscope, laser-based cofocal microscope, or atomic force microscope has paved a decisive path to-ward realizing fully-automated micro/nano manipulation operations.

The problems of handling of very small micro-optical, micro-electronically or micro-mechanical elements in nano- or micro-meter range can be solved using special micro-grippers and micro-positioners. Increasing the functionalities of such systems is one of the important trends in the modern micro-system technology. However, the majority of the micro-grippers already developed realize only a rotational movement of the gripping arms [26].

The primary function of a micro-gripper with in micro-assembly procedures is to provide high resolution grasping of minute parts in precision environment. The irregularities in size and texture of the objects add to the complexity and challenges to the developers to acquire high accuracy and controllable grasping operation. These requirements are paramount to avoid significant damage to objects which are known to be sensitive to external forces and perturbations. There are various researches have been carried out in micro-gripper [27-34].

This paper describes the development of a micro-gripper mechanism capable of delivering high precision and fidelity manipulation of micro objects utilizing compliant mechanism concept. The size and performance of the gripper have been improved due to the implementation of flexure hinge and cantilever beam structures into the mechanism design. This approach also provides the gateway to address the underlying impediments into realizing monolithic grasping mechanism. The implementation of parallel grasping scheme on the mechanism serves to enhance the grasping performance which culminates into high efficiency interaction between the gripper jaws and the object. The preliminary modeling of the gripper was realized via the combination of Pseudo Rigid Body Model (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 suit the specifications. Model refinement was subsequently conducted utilizing Finite Element Analysis (FEA).

Motivation

Recently, micro-manipulation is an important area of research in academia and industry. A number of micro-scale parts have been successfully developed using several techniques such as photolithographic and X-ray lithographic micro-fabrication techniques. Although the advancement in micro-manipulation and micro-fabrication have been steadily moving forward, the emergence of fully functional device consisting of several individual parts has yet to be fully realized due to inability of manipulating small parts and performing extensive micro-/nano-assembly operations. Once developed, the micro-manipulator will provide significant improvement in dexterous handling of an object and could indispensably transform various fields such as medical, biotechnology, manufacturing to name a few.

There are several essential design considerations and challenges arise in developing a gripper mechanism that operates within limited workspace. The inability of rigid hinge based gripper to meet the requirement of high accuracy object manipulation which involves pick and place operations, part maneuvering for insertion, bonding and mounting process requires a different modeling strategy that incorporates compactness, high compliance motion and controllability attributes.

Several types of micro-grippers have been established utilizing the concept of compliant mechanisms. These are generally based on the principle of generating motion solely based on elastic deformation exploiting the flexure in place of conventional joint. In this research, two most popular approaches have been adopted to realize the concept namely cantilever beam structure and flexure hinge which can be found in literatures [35]. While both concepts practically solve the nonlinearity and coulomb friction of the mechanism, there are still several limitations inherited in each approach. Flexure hinge application is constrained to a limited range of angular motion which is influenced by the geometry and material properties of the flexure hinge with a tendency to produce nonlinear deflections. A cantilever structure suffers from the inability to produce parallel motion, even though providing significant advantage of linear trajectory while operating within an elastic range.

Micro-grippers adopting the compliant-based structure are designed to generate variable contact forces while maintaining the mechanism in elastic region. Other requirements such as gripping behavior, structural compliance, and motion accuracy are also critical in designing process. Often these sets of specifications are difficult to be met by one individual approach such as cantilever beam or flexure hinge, since each possesses rather distinctive advantages and limitations. It is anticipated, however, that by unifying these two concepts, the new mechanism will provide a significant improvement on micro-handling operations. The extensive studies on planar parallel manipulators over the years have also contributed to the enhancement on micro-manipulator dynamic response which will serve as the foundation in realizing high precision parallel-based micro-grasping mechanism [36, 37].

Design Specifications

When considering the operation of a micro-gripper, one of the major concerns is pertaining to the object delicateness and fragility which become significant in micro-world. The stiffness of the manipulator will reflect the accuracy required to meet the desired position and force control. The gripper must therefore exhibit low gripping impedance. Otherwise small perturbation in motion can generate large change in grasping forces. The introduction of passive compliance through the implementation of spring motion in mechanism joints offers additional benefits to active compliance, particularly in impact, sudden unexpected motion behavior, and contact induced vibration [38]. The flexure hinge and cantilever beam configuration become indispensable which have the capacity in delivering this requirement.

The material should also display a reasonable compatibility with variety of objects where in small elastic module is preferable to avoid potential damage or defect to the objects. In addition, application of compliant structure simply means that it is essential for the material to allow extreme deformation within elastic region. Current trend of miniaturization of devices consequently reduces the length, width, and thickness and other geometrical properties which will have negative impact on the contact force per unit deflection, maximum force, and allowable deflection. Therefore, manipulation of material properties will allow in overcoming these geometrically imposed limitations. Ultimately, the greatest advantage comes from high ratio of yield strength to elastic modulus termed “resilience”. Higher resilient materials are able to withstand greater deflection and generate higher forces while exhibit high passive compliance. This indicates that material selection is one of the crucial aspects in accomplishing a good compliant mechanism design. Table 1 provides some common materials along with their mechanical properties, respectively. It is seen that Al7075T6 would be satisfactory for the micro-gripper design.

Different objects require specific gripping behavior to achieve high accuracy handling performance. Optical fiber handling for instance requires decisive handling operation whereas if the gripping force exceeds the specified limit, stress may develop on its core leading to degeneration of its profile and ultimately causing fiber fatigue or compression damage [37]. One of the practical solutions to overcome these issues is via appropriate flexure hinge design as it is currently the most effective way to provide accurate motion and control. The incorporation of cantilever structure adds additional benefits to the design where the flexure deformation limits can be extended without affecting its fatigue life cycle, since the beam spring structure can generate considerably large deflection under elastic limit with the advantage of minimized stress concentrations [39].

During the gripping process reaction forces act at the contact points between the gripping arms and the gripped object. In the case of micro-parts with curved or especially with circular surface such as micro-lenses the reaction forces act perpendicular to the object surface resulting in two orthogonal forces being generated as shown in Fig. 1. The X-component of the reaction force holds the gripped object between the gripping arms. The Y-component of the reaction force however acts parallel to the longitudinal axes of the micro-gripper and pushes the gripped object out of the gripping arms. This negative effect can be avoided by parallel mechanisms which exhibit motion only in the direction normal to the objects, the gripping process is realized without Y-component of the reaction force (Fig. 2), and hence ensuring a reliable grasping process. In addition, this method may also guarantee a slippage free manipulation, a more appropriate stress distribution around the surface of the object, and leading to improvement of force control scheme.

Figure 3 shows the process of performing high precision grasping of micro-object. Firstly, the micro-gripper will be positioned within the grasping domain then both jaws will move gradually in lateral mode until each of them come into necessary contact with the object and finally the jaws perform sub-micrometer motion to firmly hold the object into position without slippage. This will enable a subtler force to be exerted on the object while maintaining the accuracy and stability of the micro-handling operation.

Modeling of Micro-Gripper Mechanism

There are two popular strategies in designing compliant mechanism namely kinematic and continuum mechanics-based approaches. The kinematic approach under the utilization of PRBM [7, 8, 40] has an advantage of incorporating traditional method of kinematic analysis and design of the mechanism via the transformation of the flexible segment with a rigid body equivalent linkage. With the ability to have an insight into the system behavior and motion, this will bring intuition to the behavior of the kinematic system.

The compliant micro-gripper mechanism model was performed using the Pseudo Rigid Body Model (PBRM) concept and classical cantilever beam theory to simplify the model and to predict the mechanism response under prescribed input motion. The model will subsequently undergo optimization procedure within FEA software to obtain the optimal configuration of compliant micro-gripper mechanism. Fig. 4 illustrates the full geometrical model of the mechanism which encompasses several rigid links interconnected by flexure hinges that represent the joints to constraint and govern the essential motion of the gripper. Due to symmetrical only half model will be considered. Fig. 5 illustrates the design variables of the compliant parallel micro-gripper mechanism.

The application of PRBM is dedicated for model simplification via the transformation of flexible segment into equivalent rigid body mechanism which consists of rigid joint and torsional spring as shown in Fig. 6. Classical kinematic analysis can therefore be implemented to facilitate the modeling process. Furthermore, the mechanism response can be predicted prior to simulation procedure. A parallel motion for both of the gripper’s jaws will ensure high accuracy grasping operation on the micro objects.

The model kinematics comprises several rigid bodies joined together by rigid hinges with accompanying torsional spring as shown in Fig. 7. The structure beam spring can be accurately modeled by employing the existing PRBM as shown in Fig. 8. This will enable the section to be transformed into parallel mechanism. The kinematic analysis can then be performed based on several predetermined parameters denoted below. Due to symmetrical configuration, only the half section is considered:

$$\Delta \leq 0.2 \text{ mm} \tag{1}$$

$$0^{o} \leq \theta \leq 5^{o} \tag{2}$$

$$\beta = 0.8517 \tag{3}$$

$$F_{out} \leq 1\text{N} \tag{4}$$

where Δ represents the maximum linear trajectory of the micro-gripper, θ is the angular displacement of the parallel mechanism, and β denotes the characteristic radius factor of the beam curvature.

The equations governing the displacement of the end beam are as follows:

$$\Delta = \beta \text{ L} \sin(\theta) \tag{5}$$

$$a = L - \beta \text{ L } (1-\cos(\theta)) \tag{6}$$

$$a \leq L \tag{7}$$

The characteristic of the cantilever beam configuration can be obtained from Euler-Bernoulli equation:

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI} \tag{8}$$

where x = direction along the neutral axis, y = direction along the transverse axis, E = Young's modulus, I = area moment of inertia, and M(x) = the bending moment in the beam.

To analyze the deformation of the beam under traverse loading, Eq. (8) is integrated twice using appropriate boundary conditions. This leads to:

$$y(x) = -\frac{1}{EI}\iint M(x)dxdx + Cx + D \tag{9}$$

$$y'(x) = -\frac{1}{EI}\int M(x)dx + C \tag{10}$$

where C and D are determined from the boundary conditions $\text{y(l)} = 0$ and $y'(l) = 0$.

By rearranging Eqs. (9) and (10), the shape parameter of the double beam element can be specified to meet the design requirement described by:

$$F_{out} = -\frac{3EI}{L^3}y(0) \tag{11}$$

The torsional spring constant of the cantilever beam and flexural hinge configurations for the compliant structure of micro-gripper mechanism can be obtained from [7, 8].

$$\text{K}_\text{b} = \beta \text{K}_\theta \frac{(\text{EI})_\text{b}}{\text{L}} \tag{12}$$

$$K_h = \frac{(EI)_l}{l} \tag{13}$$

where K_b is cantilever beam stiffness, k_h is the flexure hinge stiffness, E is the material Yong's modulus, I_l is the bending moment of the flexure hinge, l is the flexure length, k_θ and I_b represent the stiffness coefficient and the bending moment of the beam.

Structure Optimization

Engineering design optimization can be characterized as a goal-oriented, constrained, decision making process to create products that satisfy well-defined human needs. Optimization is a term that is frequently and widely used in the description and conduct of design processes for development. Broadly speaking optimization means improving or fine-tuning the design in terms of one or more performance aspects. However, there is a very specific technical meaning of optimization as a rigorous mathematical statement.

Design Optimization is a very general automated design technique. Design optimization (minimizing or maximizing) consists of certain goals (objective functions), a search space (feasible solutions) and a search process (optimization methods). The feasible solutions are the set of all designs characterized by all possible values of the design parameters (design variables). The optimization method searches for the optimal design from all available feasible designs [41, 42].

The goal of structure parameters design, which is also called dimensional synthesis, is to confirm the best geometric configuration according to objective function and geometric restriction. The optimization design is mathematically modeled as follows and Fig. 9 depicts the design optimization flow chart of the compliant micro-gripper mechanism.

Design Variables

The pre-assigned design parameters are the length (L_i) of each flexible segment and the thickness (T) of the micro-gripper compliant.

Objective Function

The optimal design problem involves determining the best geometrical configuration for maximizing the magnification factor (B) the micro-gripper compliant. The objective function F(X) and is stated as follows.

$$F(x)\colon\ Maximize\ the\ \ B=\frac{Output\ Dislpasment}{intput\ Dislpasment}=\frac{U_{out}}{U_{in}} \tag{14}$$

Design Constraints

In order to avoid materials yielding in the micro-gripper compliant mechanism, the stress is considered to be less than its material yielding strength, respectively. Hence, the strength inequality constraint on the shell and in the stiffeners beams can be expressed as,

$$\sigma_{max} \le \frac{\sigma_y}{\lambda} \tag{15}$$

where σ is the actual stress in the shell, σ_y is material yielding strength and λ is the factor of safety.

$$L_i^l \le L_i \le L_i^u \ \ i = 1{,}2{,}3, \ldots 13 \tag{16}$$

where L_i, L_i^u and L_i^l represent the i^{th} flexible segment length of the micro-gripper compliant mechanism, and its upper and lower limits, respectively.

$$T^L \le T \le T^U \tag{17}$$

where T, T^U and T^L represent the thickness, and its upper and lower limits respectively.

Results and Discussion

The finite element method has been largely used to analyze various micro and nano electro-mechanical systems (MEMS/NEMS) and in particular, to obtain and simulate the topology optimization of compliant mechanisms. The finite element analyses were implemented using the ANSYS Parametric Design Language (APDL) [43]. All the horizontal hinges are designed as identical dimensions. The same for vertical hinges are designed as identical dimensions. The mesh model is created with the element of PLANE82 for 2D analysis and SOLID 45 for 3D analysis through ANSYS FEA software. Fig. 10 shows the variations of the objective function during the optimizations process. The micro-gripper parameters are described in Table 2.

Two and three dimensional graphical representations were provided for the model to primarily observe and investigate the maximum stress concentration, relative displacement between adjacent links, output motion from the jaws, and deformations under specified load condition. The computational analysis also aims to verify the motion prediction of the mechanism during modeling stage and to ensure deflection and stress distribution occurs at designated location. The application of pseudo rigid body model and finite element analysis during model development stage is important in reducing the number of design iterations during optimization procedure to reach optimum size, amplification ratio and parallel output trajectory for the mechanism.

Fig. 11 demonstrates the range of attainable displacement between the gripper’s jaws which exhibits both parallel and identical trajectory. This model was finalized after a few design iterations on the geometrical parameters of the gripper.

Fig. 12 represents the von Mises stress acting on the model. It can be observed from the analysis that the stress distribution was only localized along the flexure hinge and bias spring structures, while maintaining the remaining links in rigid state as represented by the dark blue color. This specification is important to avoid premature failure of the mechanism and obtaining high precision manipulation. The micro-gripper model can operate within large bandwidth which is one of the essential criteria required for diverse applications. Fig. 13 shows the output displacement versus the input force for the micro-gripper mechanism which validates the capacity of the gripper to deliver high precision and fidelity manipulation due to its linear elastic operational regime. While, Fig. 14 represents the input displacement versus the input force for the micro-gripper mechanism.

The gripper employs a separate amplification mechanism to enable sufficient output motion of the gripper’s jaws. This feature provides additional flexibility in the range of mobility of the jaws by utilizing different amplification factor to reach specified objective. The current amplification mechanism for the gripper is equal to 4.66. The gripper occupies a space of 100 mm long and 94 mm wide with 1.1 mm in thickness. The initial position of the jaws can be pre-adjusted to provide variable starting position for grasping application. This feature can maximize the overall performance of the gripper by offering the trade-off between the object size and jaws attainable travel distance which is limited by the actuator displacement capacity. This concept will allow the gripper to operate on variable size objects ranging from hundreds to tenths of microns. The simulation also confirms the ability of the gripper to demonstrate parallel motion for both of its jaws.

Conclusion

This research focused on the development of a new type of compliant micro-gripper mechanism utilizing a hybrid compliant mechanism structure concept in the design. The mechanical amplification is employed to make the gripper have a large motion range. A combination of flexure hinges and spring beam structure mechanism with appropriate mechanical transmission were utilized to develop a monolithic based compliant micro-gripper mechanism capable of generating parallel motion. Apart from the prevalent features of the compliant mechanism structure, namely zero backlash and high-resolution motion, the gripper has also demonstrated the ability to provide high accuracy grasping and parallel motion. These are two primary characteristics required in achieving high fidelity grasping operation.

The strategy of combining spring beam structure and flexure hinge concepts into the mechanism design has produced a monolithic structure that capitalizes on the inherent characteristic of both configurations while practically addressing the limitation between them. A combinatory modeling approach was adopted via the utilization of PRBM and FEA techniques. PRBM was first employed to initialize the basic configuration and geometrical model of the mechanism. The parameters obtained will then be transferred into simulation environment for conducting further optimization and refinements processes. FEA is finally carried out using ANSYS software to evaluate the static and dynamic performances of the mechanism. The compliant micro-gripper mechanism was modeled from high grade aluminum alloy Al 7075T6. The micro-gripper’s amplification factor is equal to 4.66. This compliant micro-gripper mechanism can be used in a wide range of micro and nano scale.

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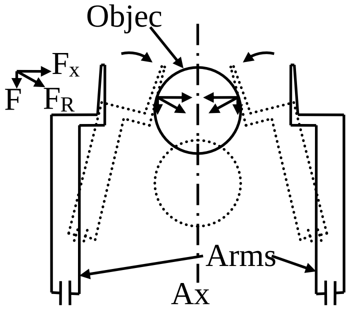


Fig. 1 Reaction forces on gripping process of unparallel gripper.

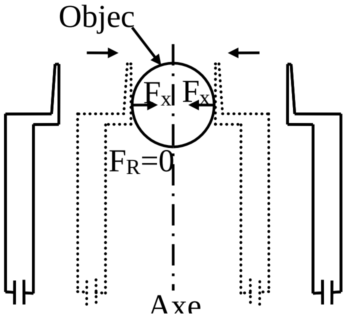


Fig. 2 Reaction forces on grasping process of parallel gripper.

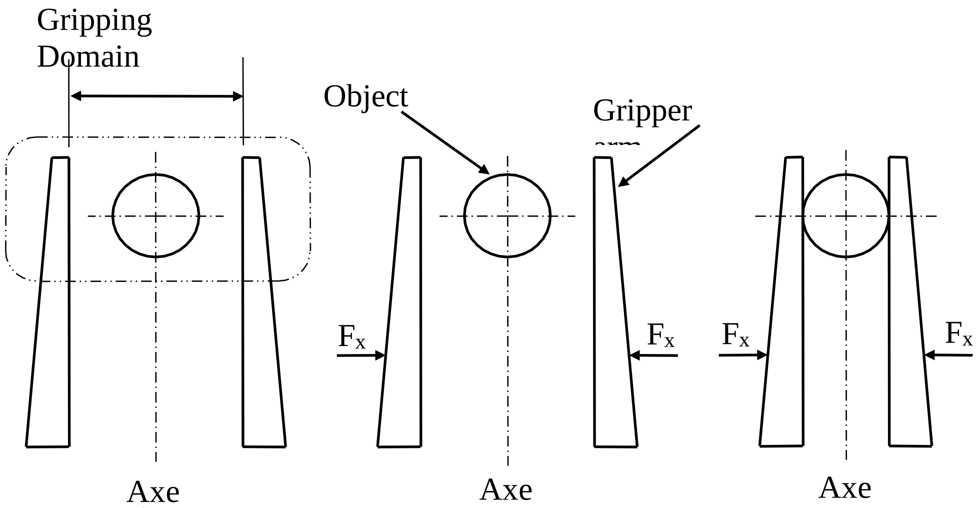


Fig. 3 The grasping of micro-object process: (a) The micro-gripper will be positioned within the grasping domain, (b) both jaws approaching the object for providing the necessary contact without damage, and (c) finally, both jaws perform sub-micrometer motion to firmly hold the object into position without slippage and damage.

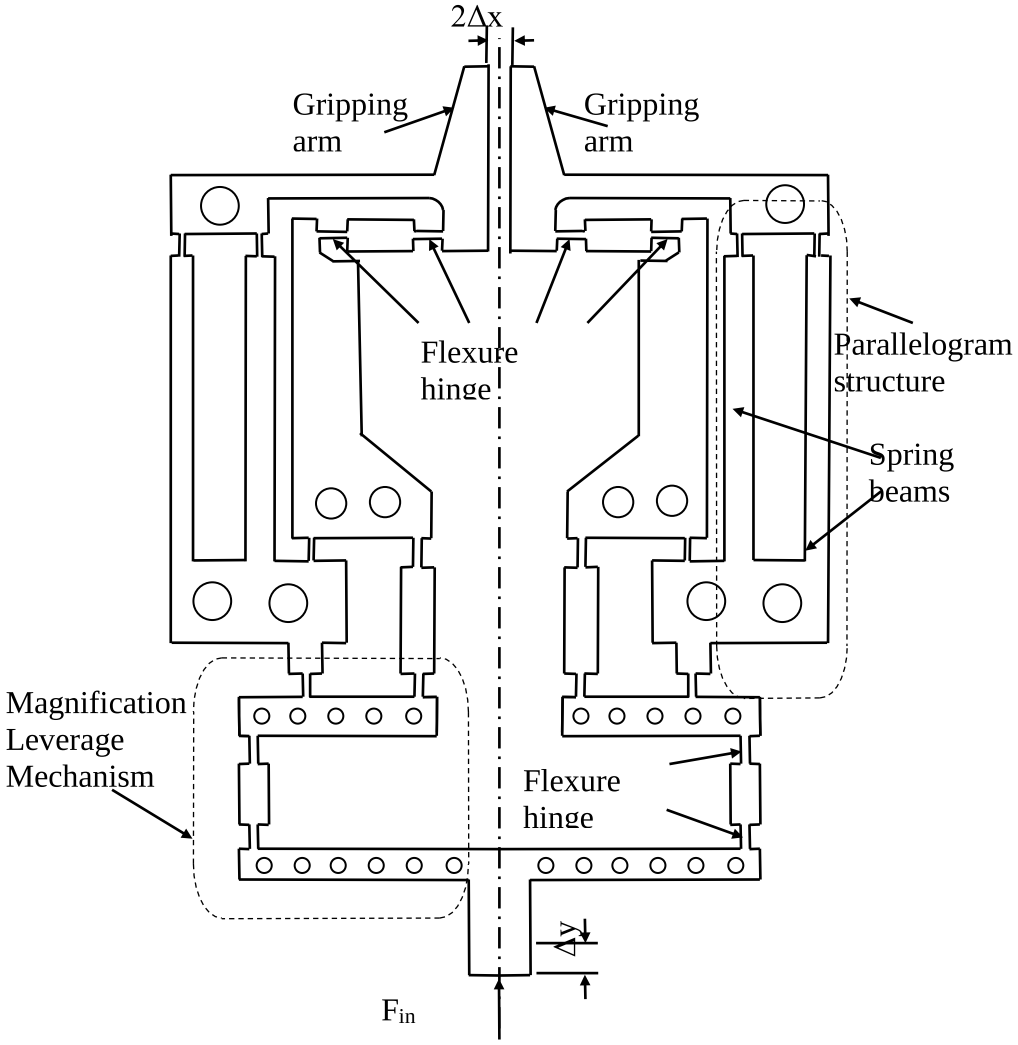


Fig. 4 The full geometrical configuration model of the compliant parallel micro-gripper mechanism.

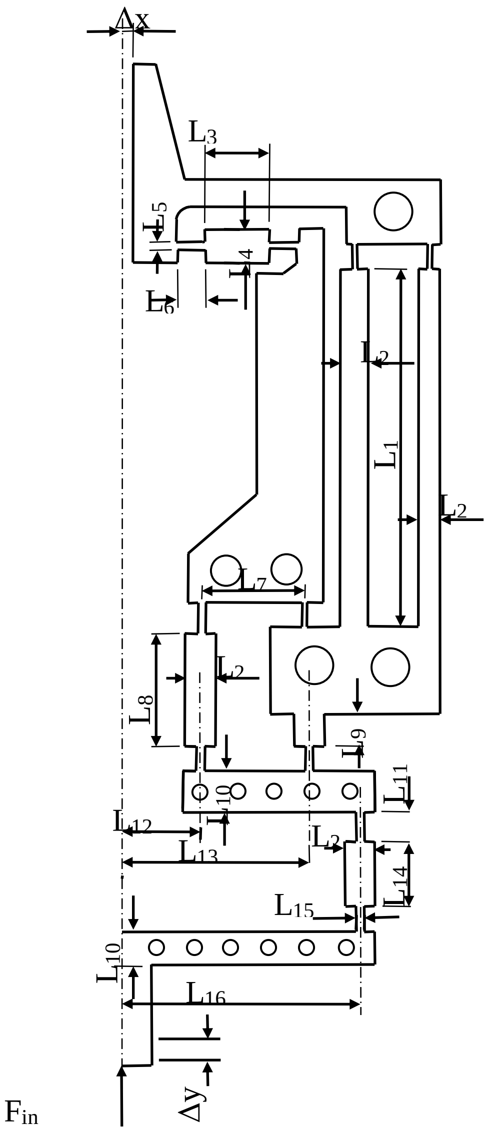


Fig. 5 The design variables of the compliant parallel micro-gripper mechanism.

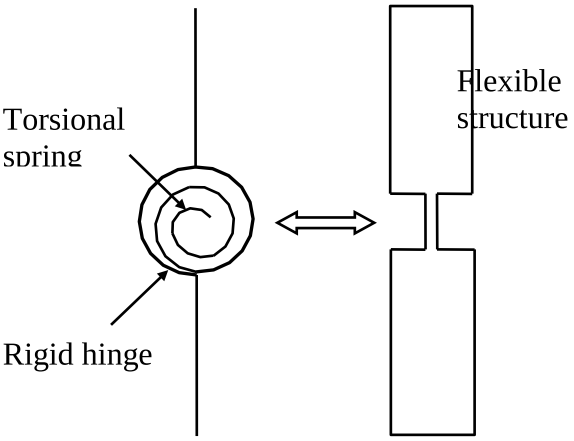


Fig. 6 Equivalent representation of the flexible structure.

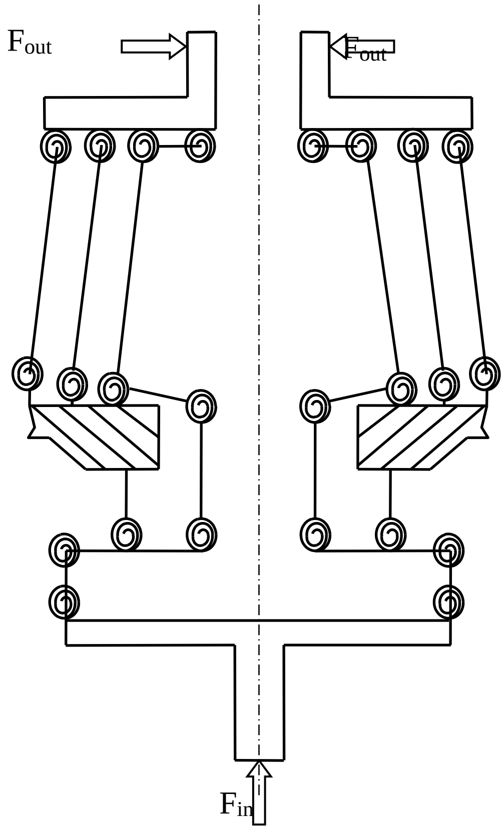


Fig. 7 Kinematic representation of the micro-gripper compliant mechanism.

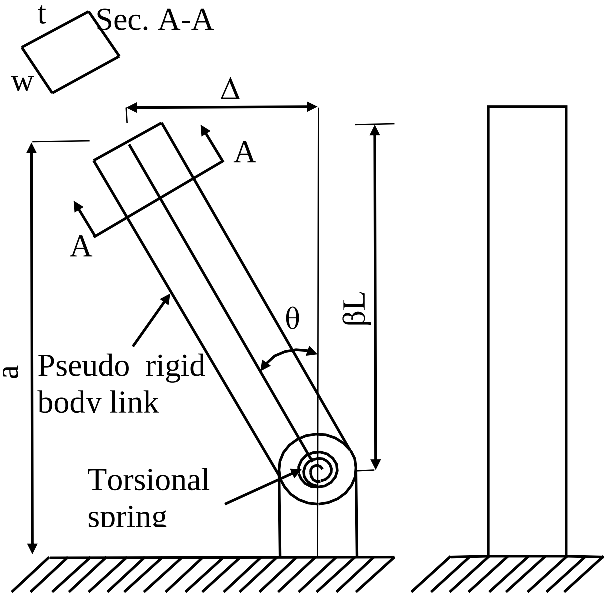


Fig. 8 Pseudo rigid body model (PRBM) of the spring beam structure.

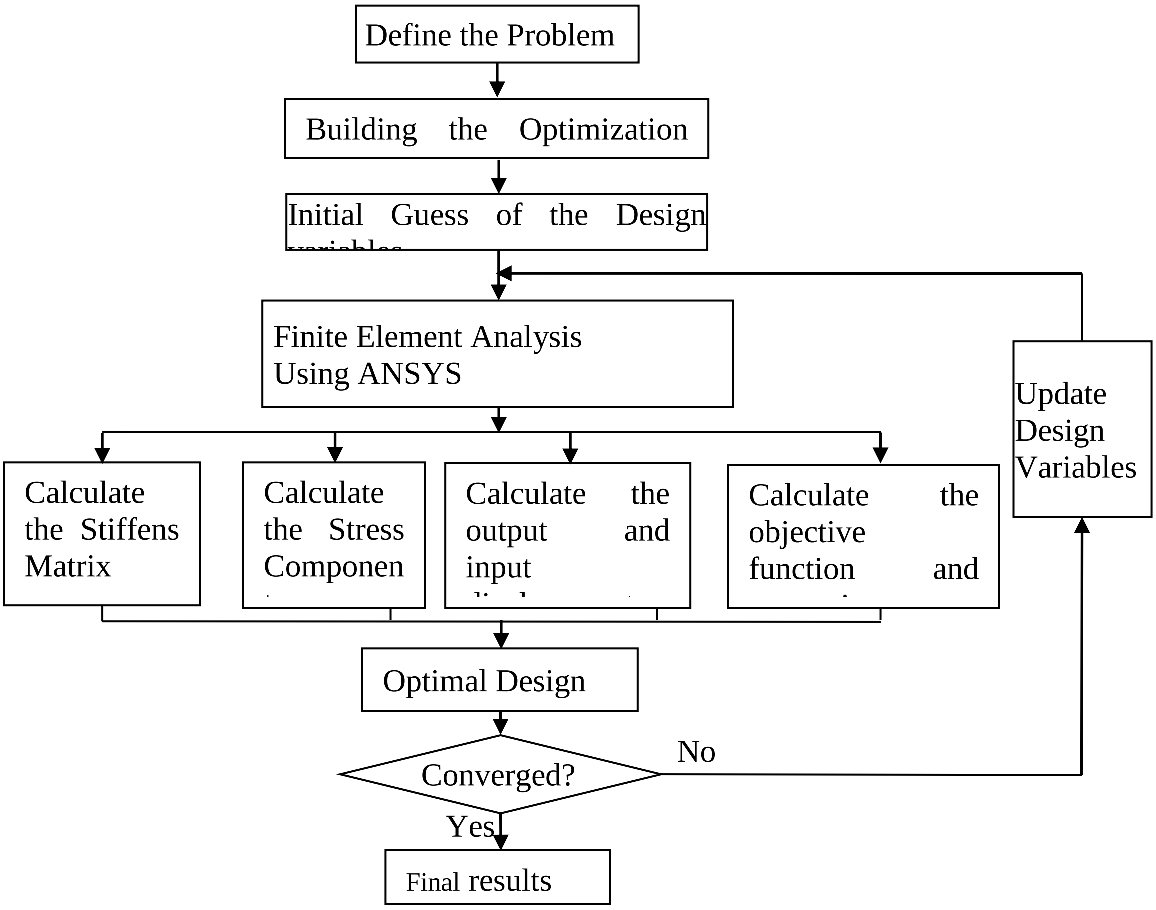


Fig. 9 The design optimization flow chart for the compliant micro-gripper mechanism.

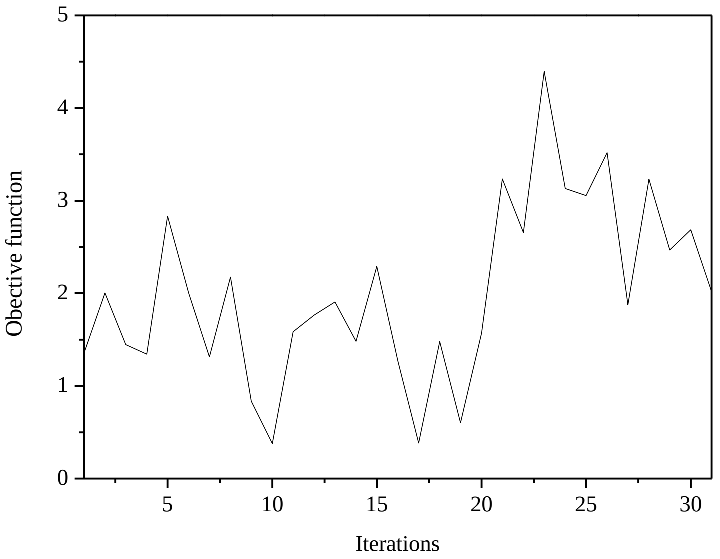
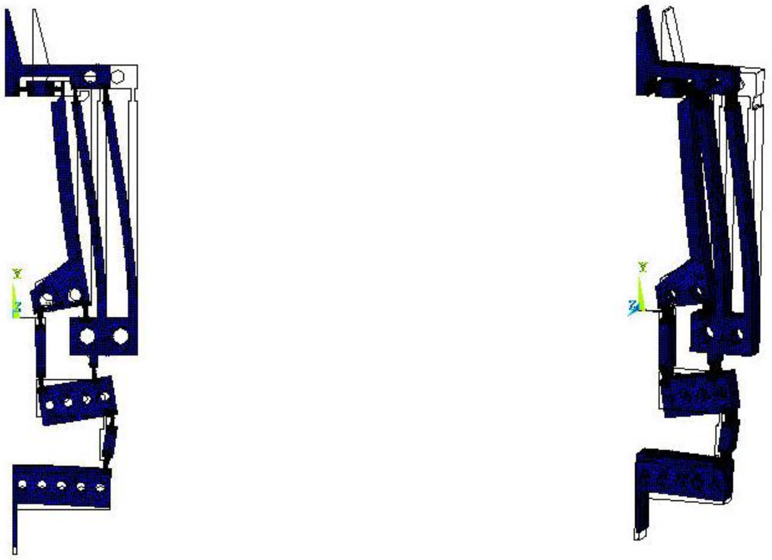


Fig. 10 The variations of the objective function during the optimizations process.



(a) (b)

Fig. 11 Finite element displacement analysis (deformed and un deformed shape) compliant micro-gripper mechanism, a) two-dimensional and b) three-dimensional.

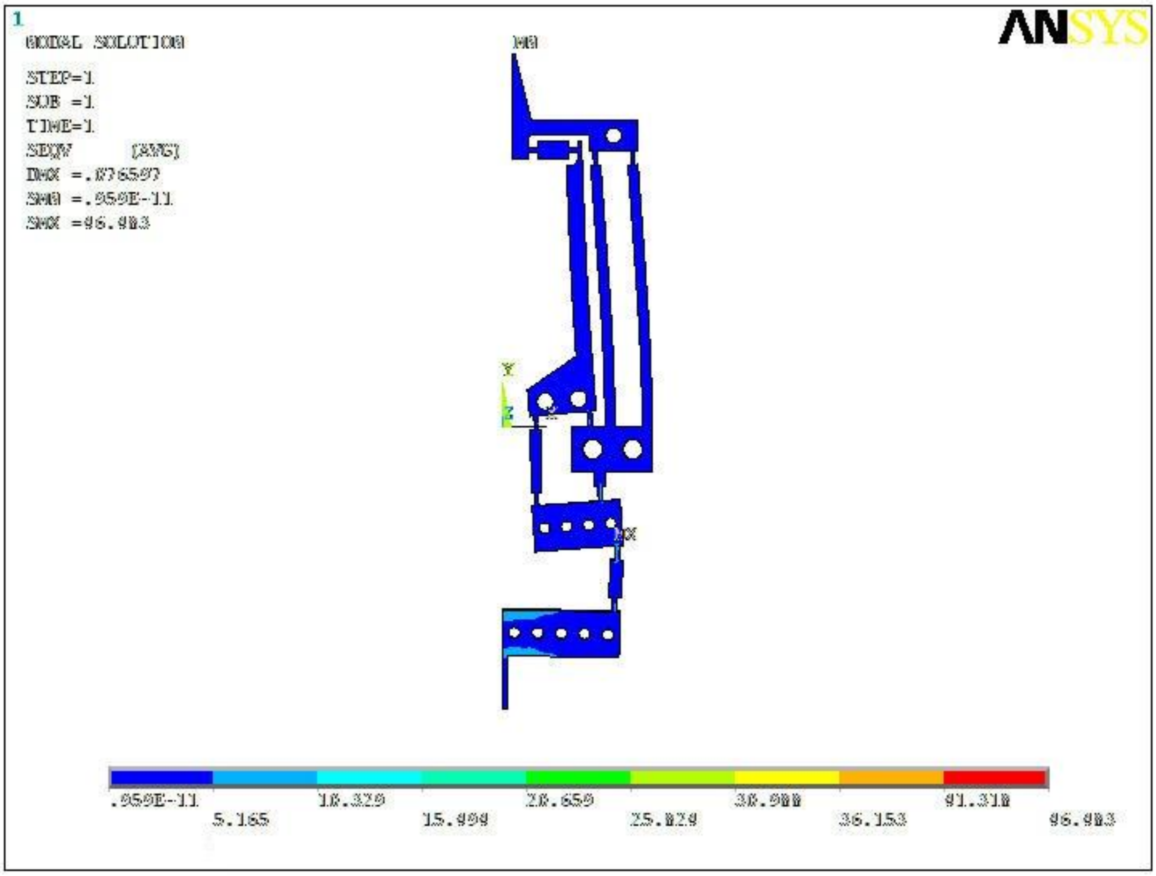


Fig. 12 von-Mises stress distribution of compliant micro-gripper mechanism.

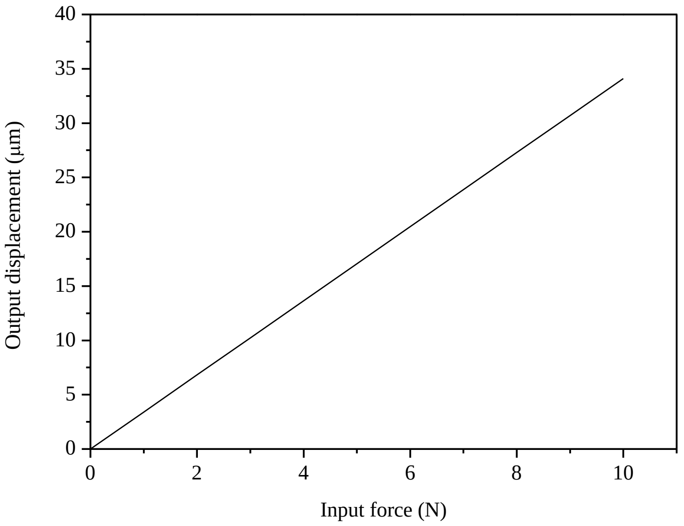


Fig. 13 The output displacement versus the input force for the micro-gripper mechanism.

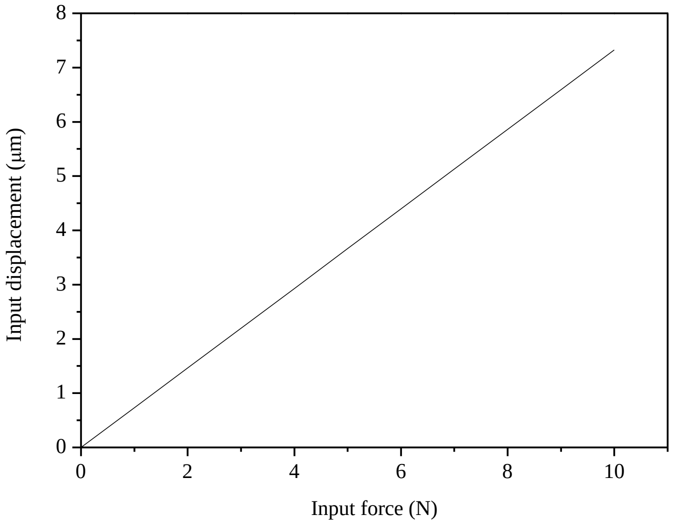


Fig. 14 The input displacement versus the input force for the micro-gripper mechanism.

Table 1 Different materials properties for micro-gripper.

Material	Modulus of elasticity E (GPa)	Poisson's Ratio ν	Density ρ (kg/m^3)	Yield stress σ_y (MPa)	Resilience σ_y /E ($\times 10^3$)
Single crystalline Silicon	200	0.27	2330	650	3.25
CuBe2	125	0.3	8250	655	5.24
Carbon steel	205	0.33	7850	345	1.68
Ti alloy	110	0.33	4700	940	8.54
Al 7075T6	71.7	0.3	2800	468	6.53

Table 2 The final dimensions value of the design variables for micro-gripper.

Symbol	Dimensions (mm)	Symbol	Dimensions (mm)
L1	39.69	L9	2.12
L2	1.51	L10	9.23
L3	4.69	L11	2.29
L4	2.68	L12	5.15
L5	0.68	L13	14.87
L6	1.52	L14	5.58
L7	8.25	L15	0.60
L8	9.51	L16	16.92