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# OPTIMAL DESIGN OF ADAPTIVE COMPLIANT MECHANISMS WITH INHERENT ACTUATORS COMPARING DISCRETE STRUCTURES WITH CONTINUUM STRUCTURES INCORPORATING FLEXURE HINGES

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## ABSTRACT

A compliant mechanism represents a single piece flexible structure which uses elastic deformation of its flexible members to achieve force and motion transmission. There are many advantages of using compliant mechanisms compared with rigid body mechanisms: Absence of wear and backlash, reduced noise, no assembly, easier maintenance and manufacturing. Previous studies of compliant mechanisms use a design process where actuators and sensors are added after the compliant mechanism is developed. This includes the determination of actuator and sensor type, orientation, size and location. In this paper a novel methodology for the optimal design of adaptive compliant mechanisms and their actuation in only one structure is represented. Hence, the structural topology of the compliant mechanism and the placement of multiple inherent actuators are simultaneously synthesized. Two different approaches during the novel design methodology are used for exemplary developing two topology optimized adaptive compliant grippers with same topology but different shape: A discrete beam like structure and a continuum structure incorporating optimal designed flexure hinges with polynomial contours. The improvement of performance of both grippers is compared regarding the adaptability and the stroke.

***Index Terms -*** Adaptive compliant mechanisms, topology optimization, shape optimization, flexure hinges, adaptive gripper

## 1. INTRODUCTION

Compliant mechanisms, unlike conventional rigid body mechanisms consisting of rigid members and classical joints, represent a single piece flexible structure which uses elastic deformation of its flexible members to achieve force and motion transmission [1]. There are many advantages of using compliant mechanisms compared with classical ones: Absence of wear and backlash, reduced noise, no assembly, better scalability, better accuracy, easier maintenance and manufacturing. Previous studies of compliant mechanisms use a design process where actuators and sensors are added after a compliant mechanism is developed including the determination of actuator/sensor type, orientation, size and location occurring outside of the automated design synthesis at the designer's option. In this paper a novel methodology for the optimal design of adaptive compliant mechanisms and their actuation in only one structure is represented. Hence, the structural topology of the compliant mechanism and the placement of multiple inherent actuators are simultaneously synthesized. Here, the actuator placement (type, orientation, size and location of the actuators) affects the structural topology of a mechanism as well as vice versa.

By embedding actuators and sensors within the compliant mechanism structure, the system can realize both sensing (via sensors) and appropriate response (via actuators and internal structure) to the unknown external environment, thus making the system adaptive. Such compliant systems are biologically inspired and hold the potential to lead to tightly integrated, highly functional, multi-purpose, adaptive systems.

In this paper we pay more attention to the problem of embedding actuators since one of the goal of the paper is to develop a compliant mechanism that is capable of achieving multiple shape states i.e. to develop a compliant system that has structural adaptability. By embedding actuators within a compliant structure, a system may be capable of producing many different shapes of its output surface i.e. a system would be adaptive. Such adaptive structures are of interest for a number of applications [2-7].

The synthesis of compliant mechanisms has been studied well in the past [8, 9], but little attention has been directed to problems related to the synthesis of adaptive compliant mechanisms [3, 10-12]. Synthesis methods developed in [3, 10, 11] focuses on determination of optimal topology of compliant mechanisms so that they can achieve the target curve profile. But these papers only focus on problems regarding changing an initial shape to one target shape, where the final target shape is determined ahead of time and specified by the designer. More over the actuators are added after a compliant mechanism is developed and they are not included in the synthesis process. These methods cannot be applied when developing a system that can respond to the unknown external environment. There are many situations where the desired shape change might not be known ahead of time and could be a function of the environment. For such applications, compliant mechanism should be adaptive and should have a controllable response with exceptional manipulability.

The algorithmic framework for an adaptive compliant system with distributed actuation and sensing within a compliant active structure has been already developed in [12]. But the proposed method often produces compliant mechanism with lot of intersections between elements as well as elements and actuators, which are very difficult (or nearly impossible) to manufacture. Beside this, intersections between elements often increase complexity and stiffness of the structure which can significantly lower the system functionality. This deficiency has motivated us to improve design methodology for the simultaneous synthesis of compliant mechanism and actuator placement. The design methodology is improved so that compliant systems (compliant mechanism with embedded actuators) without intersecting elements are obtained (unlike solutions obtained in [12]). This represents one novel approach to the synthesis of compliant systems.

Further, this paper presents two different approaches during the improved design methodology that are used for exemplary developing two topology optimized adaptive compliant grippers with same topology but different shape: A discrete beam like structure and a continuum structure incorporating optimal designed flexure hinges with polynomial contours. The improvement of performance of both grippers is compared regarding adaptability and stroke. The resulting adaptive grippers can grasp objects of widely varying shapes and could have possible application in many fields, e.g. in medicine and robotics.

## 2. MATERIAL AND METHODS

One example of an adaptive compliant mechanism with inherent actuators could be an adaptive gripper. Embedded actuators within the compliant gripper structure would provide the gripper with ability to achieve multiple grasping patterns, thus making the gripper adaptive.

Complaint mechanisms can be subdivided into two groups: mechanisms with lumped compliance [13] and mechanisms with distributed compliance [8-12]. To develop adaptive compliant gripper we use compliant mechanisms with distributed compliance [8], since the distributed compliance throughout the compliant mechanism provides a smooth deformation field, which reduces the stress concentration. The continuum synthesis approach is usually used for the design of mechanisms with distributed compliance [8, 9]. The synthesis methodology used in this approach involves two stages: generation of the mechanism topology and determination of optimum size, geometry, and shape of various constituent elements of the mechanism (dimensional synthesis).

Adaptive compliant gripper could be seen as compliant mechanism with embedded actuators. To develop an adaptive gripper, the structural topology of a compliant mechanism and actuator placement must be simultaneously synthesized.

In [14] we have developed computer-coded algorithm for synthesis of compliant mechanisms with distributed compliance, and improved the topology optimization technique in [15]. To develop adaptive compliant gripper we modify our computer-coded algorithm so that actuator placement is also included in the synthesis process. Actuators, modeled as both force generators and structural compliant elements, are included as topology variables in the optimization. We also incorporate control in the synthesis process through the use of structural orthogonality concept [12].

As the second step in the continuum synthesis approach the shape optimization of the adaptive compliant gripper is done. The exact size, shape, and geometry of each of the gripper structural elements is optimized (here the actuators are not included in the shape optimization process). As a result of the optimization procedure several very thin regions occur. It is common to replace these senseless regions using prismatic flexure hinges with semicircular contours [16, 17]. For this post optimization step, flexure hinges with 4th-order polynomial contours are used in this paper since they realize a better deformation and motion behavior of the whole compliant mechanism [18, 19].

Both the topology optimization process and the shape optimization process are described in detail in the following sections.

## 3. TOPOLOGY OPTIMIZATION

The outline of the methodology that we use for developing an adaptive compliant gripper with embedded actuators is shown in a pictorial example (Fig. 1). First the problem specifications are defined only for one gripper finger (Fig. 1a and Table 1). These includes: Size of the design domain (allowable space for the design), grasping surface (left boundary of the design domain) and number of output points (three output points are chosen to represent the output region where horizontal direction is set to be the desired direction of the output deflection), supports (the bottom boundary of the design domain – one part only), property of the material (Young modulus) from which the mechanism should be built and other constraints such as minimum value of the output deflection $d_{min,target}^{act}$ and total element length $L_t$ which is equivalent to the volume constraint. All the design parameters are given in Table 1.

Next the design domain is parameterized (Fig. 1b). The physical design space must be broken down so as to be represented by a set of variables that an optimizer can act on. The Grounded Structure Approach (GSA) [8, 12, 14, 15] is used for the parameterization. Therefore, the prescribed design domain is divided into a number of nodes, and a network of beam elements connecting these nodes serves as an initial guess. The design variables are the thickness of each element and variable that marks the element selected to be actuator; this variable has a value between 1 and the total number of elements (Table 1). The linear actuator model is used where at the ends of the beam axial force, equal to the block force [12], is applied. A thickness value of zero deactivates the element, removing it from the structure; other values represent thickness values (Table 1). It is important to note that we used partially connected ground structure (Fig. 1b) i.e. the ground structure that is not "fully connected" (not all the nodes in the ground structure are interconnected). A fully connected structure can lead to overlapping elements that are difficult to produce. Thus, certain filters (as computer-code) are used to eliminate the overlapping elements. In addition, the degree of nodal connectivity [15] is defined as well (Table 1).

**Table 1.** Design specifications for developing adaptive compliant gripper with embedded actuators

| ***Design parameters*** | |
|---|---|
| design domain | 120 mm × 80 mm |
| grid size | 5 × 5 |
| degree of nodal connectivity | 4 |
| number of beam elements | 168 |
| element modulus | $E_{\mathrm{el}}$=2.48 GPa |
| actuator modulus | $E_{\mathrm{akt}}$=500 MPa |
| actuator block force | 90 N |
| external load | 0.1 N |
| element out-of-plane thickness | 1.5 mm |
| element thickness choice | 0.5 mm, 1 mm, 1.5 mm |
| thickness of shape morphing surface | 0.5 mm |

When using the partially connected ground structure the solutions with intersecting elements are obtained [8, 14] where elements and actuators would intersect also [12]. Producing a structure with intersecting elements as well as actuators is very difficult. Moreover intersections between elements often increase complexity and stiffness of the structure which can significantly lower the system functionality. This deficiency has motivated us to improve the existing topology optimization technique [12] so that the intersections between elements as well as actuators would be eliminated in the optimization process. We apply the same ideas in [15], but now for the problem of synthesis of adaptive compliant gripper with embedded actuators. All the parameters regarding the parameterization are given in Table 1.

After the parameterization is done, search method is applied to find the optimal compliant mechanism with embedded actuators. Because of the broad design space and number of elements, topology synthesis problems are solved with optimization methods. The goal of the optimization in the synthesis of compliant mechanisms with embedded actuators is to minimize the actuator number and maximize structural adaptability of a compliant system (maximize controllability [12]) while meeting given constraints. By maximizing controllability gripper will be able to achieve multiple grasping patterns of its shape morphing surface. Three actuators are required minimally to fully control the three output points (Fig. 1a). The objective function we used for the synthesis of the adaptive compliant gripper with embedded actuators is:

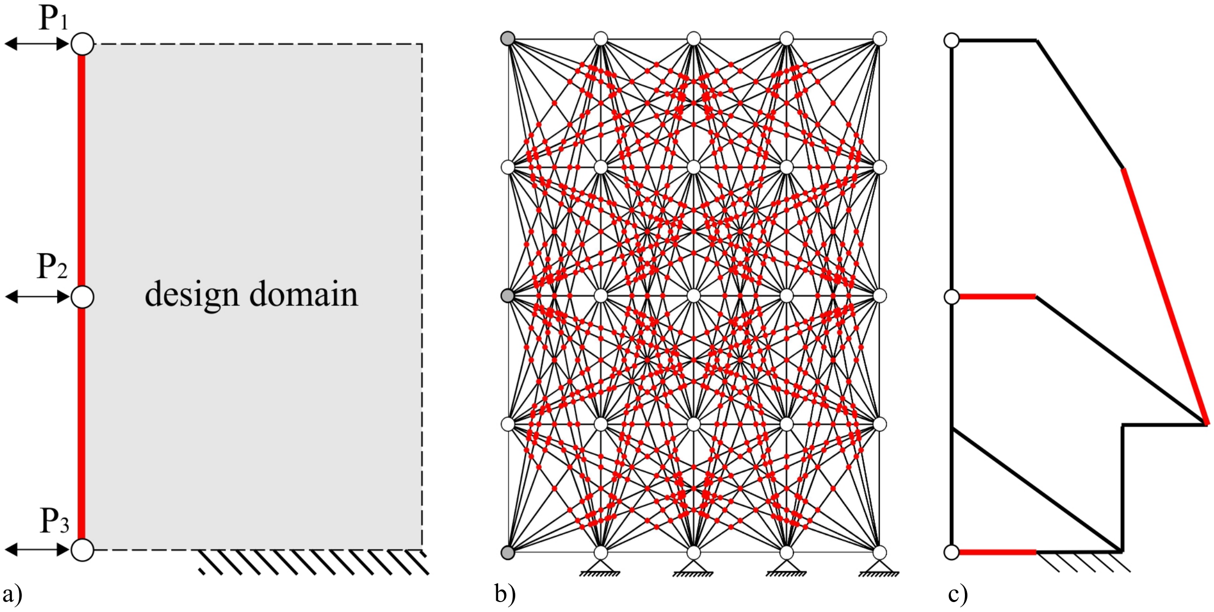
$$\textbf{maximize}\begin{bmatrix} \eta_C - w_1 \cdot \left(d_{min,target}^{act} - d_{min}^{act}\right) - w_2 \cdot \left|d_{max}^{ext}\right| - \\ -w_3 \cdot \left|L_t - L_{target}\right| - w_4 \cdot n_{int} \end{bmatrix}. \quad (1)$$

Where: $\eta_C$ is controllability [12], $w_1$, $w_2$, $w_3$ and $w_4$ are relative weighting constants, $d_{\mathrm{min,target}}^{act} = 1\,\mathrm{mm}$ is the minimum value of the output deflection, $d_{min}^{act}$ is the displacement of the output points [12], $d_{max}^{ext}$ is the displacement of the output points caused by external loading (the external load is applied at all three output points, all at once) [12], $L_t$ is total element length, $L_{target} = 721.1$ mm is the desired total element length [12] and $n_{int}$ represent the total number of intersections in the structure [15].

All objective function terms and constraints are calculated from the results of the linear finite element analysis (FEA), implemented in the computer-coded algorithm.

When the parameterization is discrete i.e. elements are either on or off, the discrete optimizations methods are used, of which Genetic Algorithms (GA) [20] are applied here. The genetic algorithm parameters used in the synthesis of the adaptive compliant gripper are: initial population of 200 designs, total number of 1000 generations, roulette selection function, crossover probability of 95%, elite count of 2 members, and mutation probability of 9%.

To obtain the adaptive compliant gripper with embedded actuators more than twenty GA's are run. The optimization process starts with 168 beam variables and total number of 1664 intersections in the initial ground structure (Fig. 1b). Figure 1c shows the result. This obtained solution contains the compliant structure in which some of the elements are eliminated and some chosen as actuators in the process of optimization. The remaining elements together with elements selected to be actuators define the optimal topology of the adaptive compliant gripper finger. High controllability ($\eta_C$=97.57%) of a compliant system is achieved. Unlike solutions in [12] here the compliant system without intersections is obtained (Fig. 1c).



a) b) c)

**Fig. 1.** The steps in the synthesis methodology: a) problem specifications; b) parameterization (intersections between elements are indicated by red dots); c) optimized topology of adaptive compliant gripper finger with embedded actuators (actuators are indicated by red lines)

Based on the obtained solution (Fig. 1c) 3D solid model of the adaptive compliant gripper finger with embedded actuators was designed (Fig. 2). Instead of using real actuators, here the actuators were modeled as thin elastic elements (in a form of a spring) that allow the actuation (Fig. 2). We decided to model only one finger of the gripper as the fingers in two-fingered or multi-fingered gripper would have the same behavior.

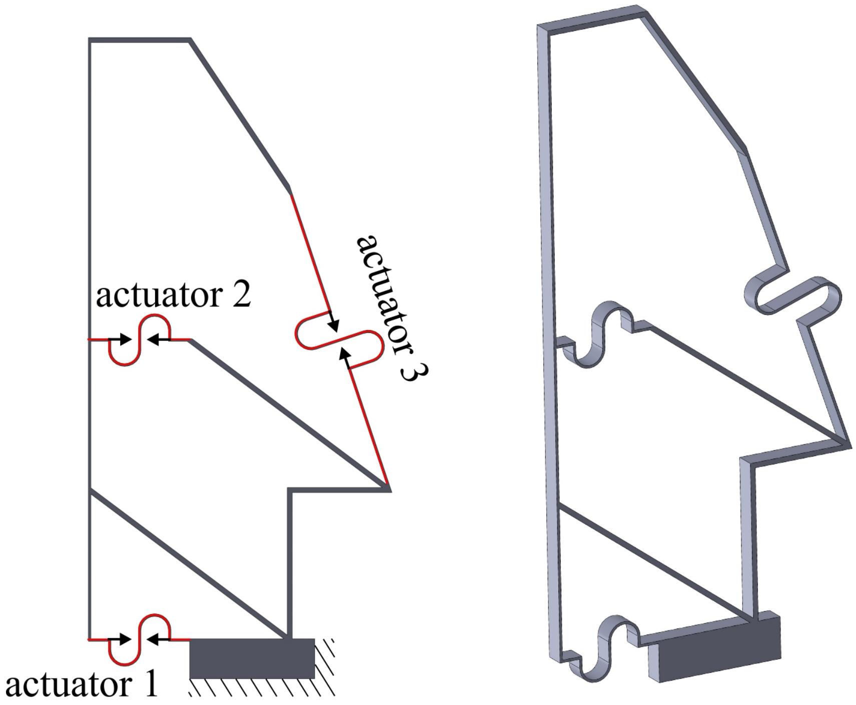


**Fig. 2.** Design of adaptive compliant gripper finger with embedded contracting actuators

## 4. SHAPE OPTIMIZATION

After obtaining the optimal topology of the adaptive compliant gripper finger with optimally placed inherent actuators the shape optimization is performed. In the shape optimization process the exact size, shape, and geometry of each of the beam elements is optimized. The shape optimization determines the optimal geometry for a given topology of the structure. Usually the goal in the shape optimization process is to maximize the stiffness or to minimize the stresses in the structure.

When designing a compliant mechanisms, the goal in the shape optimization is to find the balance between the compliance and the stiffness of the structure: The compliant mechanism should have adequate flexibility to undergo desired deformations under the action of applied forces and adequate stiffness to withstand external loading. Many researchers developed different kind of methods for shape optimization of compliant mechanisms [21-24]. Beside this, there is a number of commercially available FEM software's that have a module for shape optimization, some of them are ANSYS, COMSOL, ABAQUS etc.

For shape optimization of the adaptive compliant gripper finger we use ABAQUS. ABAQUS software within its environment has a module for shape optimization. In ABAQUS shape optimization begins with a fine element model of the structure. During the optimization the nodes on the boundary (of the region selected for the shape optimization) are displaced in order to achieve an objective (minimization of stress on the surface for example). After the optimization procedure converges a new shape of the structure is obtained.

As regions for shape optimization of the adaptive compliant gripper finger, only the beam elements are selected (Fig. 3a), while the support, the grasping surface of the gripper and the actuators are not included into the optimization process. The objective function we used for the shape optimization of the adaptive compliant gripper finger with embedded actuators is:

$$\textbf{minimize}\left[U_{A_1}+U_{A_2}+U_{A_3}\right]. \tag{2}$$

Where: $U_{A_1}$ is strain energy of the structure measured when actuator 1 is active, $U_{A_2}$ is strain energy of the structure measured when actuator 2 is active and $U_{A_3}$ is strain energy of the structure measured when actuator 3 is active. Thus the goal in the shape optimization of the adaptive compliant gripper finger is to minimize the strain energy of the adaptive gripper structure which is equivalent to maximizing the stiffness of the gripper structure. The stiffness of the gripper structure is maximized so that the gripper could realize a sufficient gripping force and is be able to withstand the external loads (the maximal and minimal possible values of the stiffness are specified). The resulting shape optimized adaptive compliant gripper finger with embedded actuators is shown in Figure 3b.

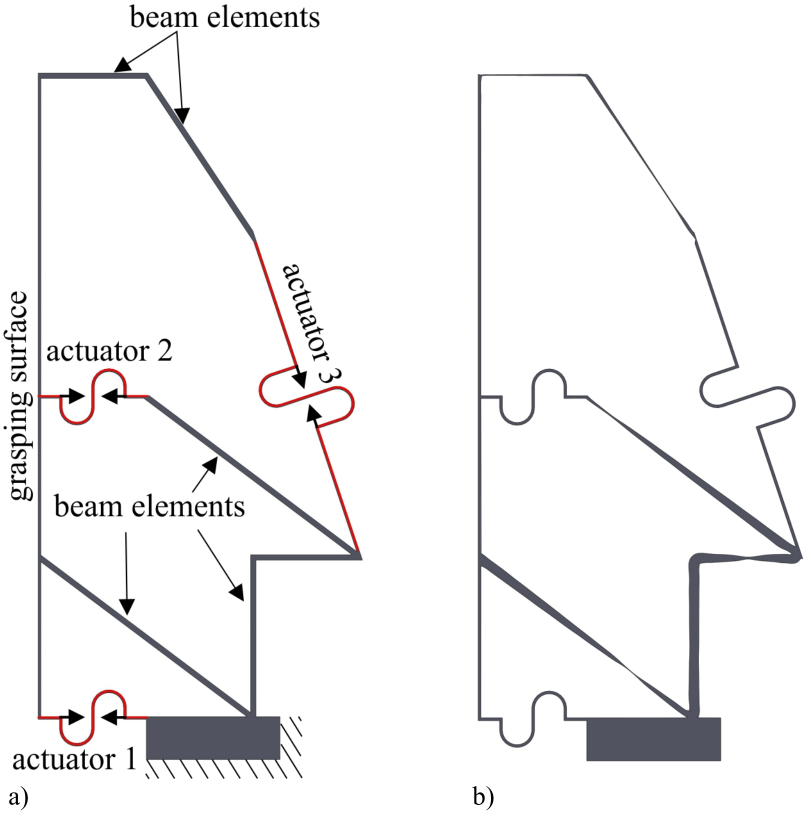


**Fig. 3.** a) Selected beam elements of the adaptive compliant gripper finger for shape optimization; b) shape optimized adaptive compliant gripper finger with embedded actuators

## 5. INCORPORATION OF 4th-ORDER POLYNOMIAL FLEXURE HINGES

In contrast to the mechanisms discussed in this paper, in compliant linkage mechanisms the flexibility is achieved only by flexure hinges, which fulfill the function of conventional revolute joints but are limited to small angular deflections of a few degrees. For guiding and transfer tasks in precision systems of microsystems technology, precision engineering or metrology, mostly prismatic flexure hinges with basic cut-out geometries are used as material coherent revolute joints realizing a plane motion.

Because of the material coherent pair, flexure hinges have a small motion range, which is limited by the allowable stress. In addition, the load-dependent shift of its axis of rotation is disadvantageous. The demand for larger angular deflection and a low shift of the rotational axis results in very complex flexures or an increased number of joints in the mechanism. Special optimized flexure hinges with a simple cut out based on polynomial functions are not state-of-the-art (Fig. 4).

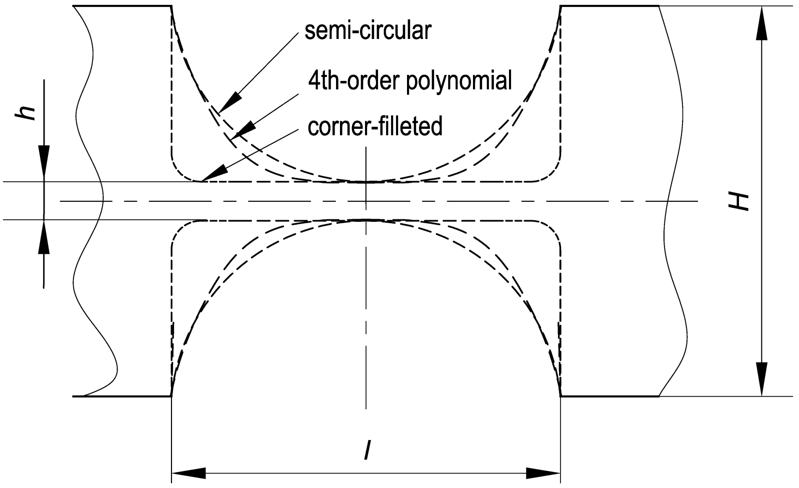
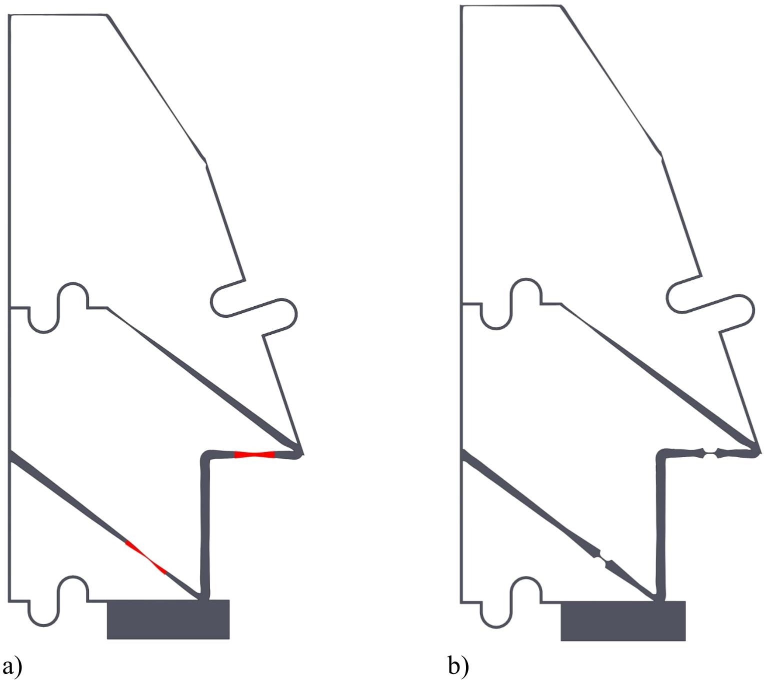


**Fig. 4.** Parameters of a flexure hinge with three different contours

Regarding the replacing of thin regions as a result of the topology optimization mostly semi-circular flexure hinges are used. In our own studies it is shown that no specific flexure hinge contour is optimal in general to realize a precise motion, because the motion and deformation behavior of compliant linkage mechanisms depend on several geometrical hinge parameters to the same degree [19]. Accordingly, the post optimization synthesis represents a multi-criteria optimization problem too. It is also found that 4th-order polynomial contours are particularly suitable to realize both precise motion and large stroke. Therefor these polynomial contours are chosen to incorporate flexure hinges instead of two thin regions in the gripper (Fig. 5).



a) b)

**Fig. 5.** Shape optimized adaptive compliant gripper finger with embedded actuators: a) with original thin regions; b) with incorporated flexure hinges based on 4th-order polynomial contours ($l = 1.5\ H$; $h = 0.1\ H$)

## 6. DISCUSSION

To investigate adaptability of the both compliant gripper fingers (one with a discrete beam like structure and one with a continuum structure incorporating optimal designed flexure hinges with polynomial contours) two different shapes of the gripping objects FEM simulations were performed (now ANSYS software was used). As boundary condition fixed support was applied at immobile part of the gripper fingers (Fig. 6a and Fig. 7a). To simulate the contraction of the actuators, as input a displacement of ±4.5 mm (stroke of actuator) in the direction of the actuators axis was introduced at the both ends of the all actuators (Fig. 6a and Fig. 7a). In this paper we simulate actuators that contract, but extension actuators could be simulated as well. To show the capability of the gripper fingers to produce multiple shapes of their shape morphing surfaces the FEM simulations were performed without any grasping object (Fig. 6 and Fig. 7).

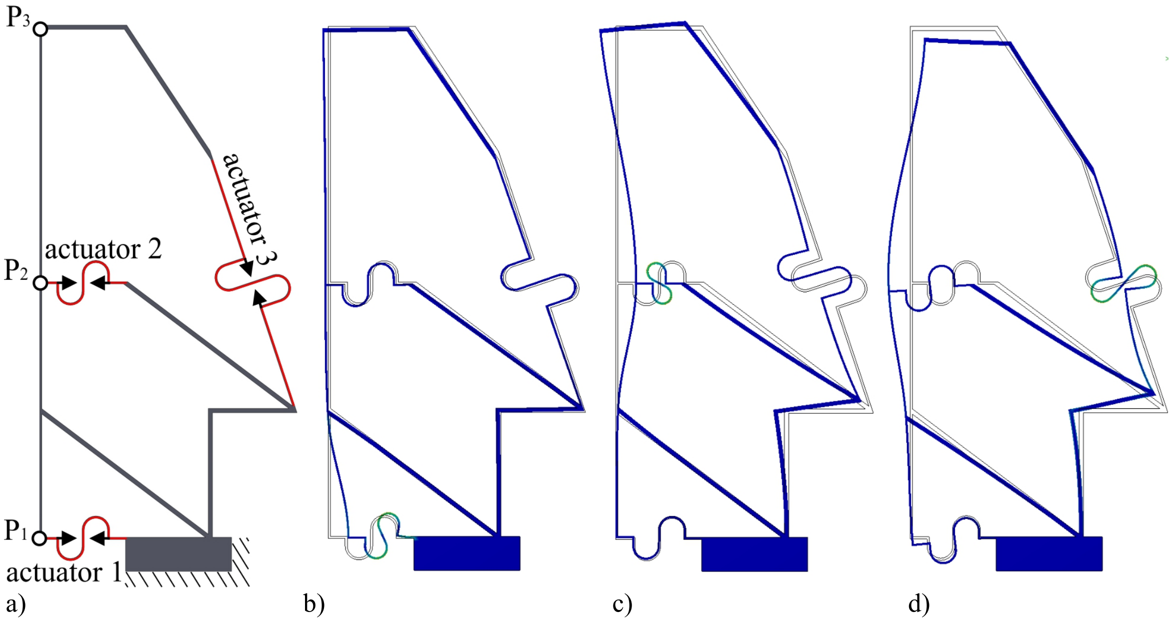


**Fig. 6.** Design of adaptive compliant gripper finger with embedded contracting actuators and discrete beam like structure (a) and FEM results when actuator 1 (b), actuator 2 (c) and actuator 3 (d) is active

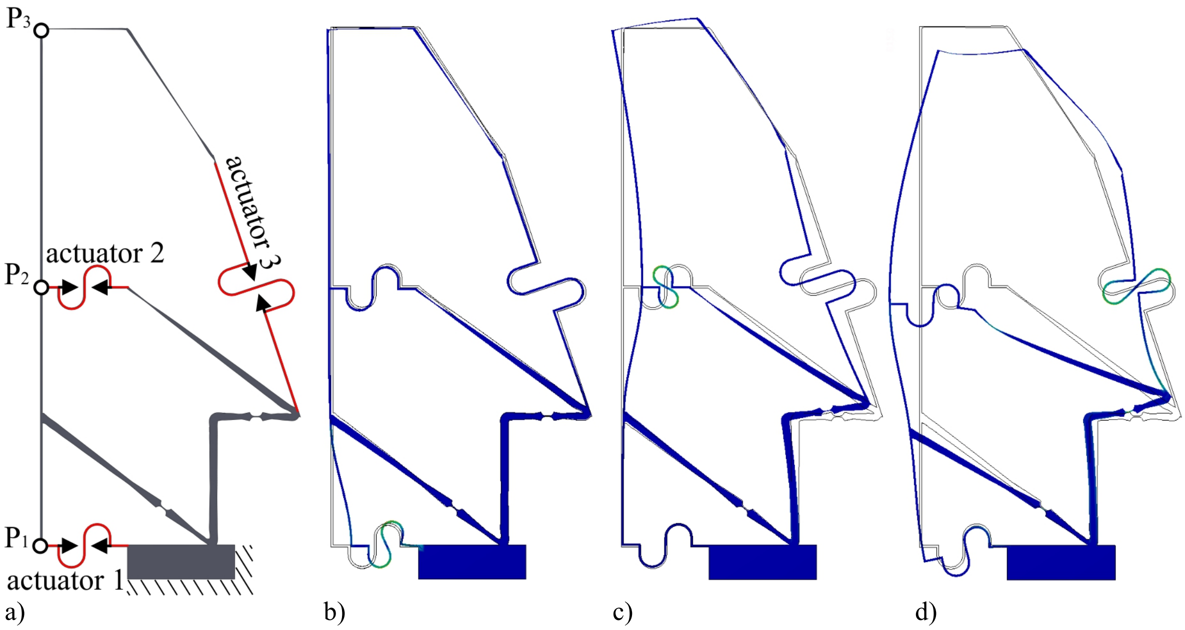


**Fig. 7.** Design of adaptive compliant gripper finger with embedded contracting actuators and continuum structure with polynomial flexure hinges (a) and FEM results when actuator 1 (b), actuator 2 (c) and actuator 3 (d) is active

The FEM results show that two main grasping patterns could be created in the case of both gripper fingers: ‘convex’ (Fig. 6c and Fig. 7c) and ‘concave’ patterns (Fig. 6d and Fig. 7d); when actuator 2 is active an object of convex shape could be grasped (Fig. 6c and Fig. 7c), and when actuator 3 is active an object of concave shape could be grasped (Fig. 6d and Fig. 7d). Also actuator 1 could be used to accommodate the grasping surface of the gripper fingers to different irregular shapes of the grasping object. Different grasping patterns could be also achieved with different combinations of active actuators.

To compare the performance of the both grippers (one with beam elements and one with polynomial flexure hinges), regarding the adaptability and the stroke, the displacement of the output points ($P_1$, $P_2$ and $P_3$ in Fig.6 and Fig. 7) of the both gripper fingers were determined for the case when actuator 1, 2 or 3 is active. The displacement of the output points were determined only in the horizontal directions (since this is the desired displacement direction of the output points). The results are given in Table 2 for the case when actuator 3 is active.

**Table 2.** The displacement of the output points of the gripper finger with a discrete beam like structure and gripper finger with optimal designed flexure hinges with polynomial contours when actuator 1, 2 and 3 are active

| **Gripper finger** | **output points** | **actuator 3** |
|---|---|---|
| | | **displacement (mm)** |
| gripper finger with beams elements | 1 | -0.41 |
| | 2 | 5.24 |
| | 3 | -3.27 |
| gripper finger with polynomial flexure hinges | 1 | -1.05 |
| | 2 | 7.12 |
| | 3 | -4.15 |

The performance of the two gripper fingers (one with beam elements and one with polynomial flexure hinges) were compared regarding the adaptability and the stroke. The results show that for the same stroke of actuator 3 the gripper finger with polynomial flexure hinges (Fig. 7d) realize a higher displacement of the output points than the gripper finger with beam elements (Fig. 6d). This means that gripper with polynomial flexure hinges could grasp objects that are more concave in their shape. Thus, the gripper finger with polynomial flexure hinges can realize better adaptability regarding the gripper finger with beam elements.

## 7. CONCLUSIONS

This paper presents a novel methodology for the optimal design of adaptive compliant mechanisms and their actuation in only one structure. Here the structural topology of the compliant mechanism and the placement of multiple inherent actuators (their type, orientation, size and location) are simultaneously synthesized. By embedding actuators within a compliant structure (compliant mechanism) it is possible to develop adaptive system i.e. a compliant system that is capable of producing many different shapes of its output surface. Such adaptive structures are of interest for a number of applications.

The existing algorithmic framework for adaptive compliant system with distributed actuation often produces a compliant system with intersecting structural elements as well as actuators which are very difficult to manufacture. Moreover, the intersection between elements often increases complexity and stiffness of the structure which can significantly lower the system functionality. Thus, the design methodology is improved so that compliant systems without intersecting elements are obtained. This represents one novel approach to the synthesis of adaptive compliant systems.

The novel approach was used for developing adaptive compliant gripper finger with embedded actuators that can grasp objects of widely varying shapes. The optimal topology of the gripper finger without intersecting beam elements and with embedded actuators was obtained. The shape optimization of the gripper finger is done as well. The exact size, shape, and geometry of each of the gripper beam elements is optimized. Two thin regions of the shape optimized gripper finger were replaced with optimal designed flexure hinges based on 4th-order polynomial contours which are a good compromise to realize both a high precision and a large stroke.

The FEM results demonstrate that by embedding actuators within the gripper finger structure the two developed adaptive compliant fingers (one with discrete beam like structure and one with continuum structure incorporating optimal designed flexure hinges with polynomial contours) have ability to produce many complex grasping patterns (gripper finger can accommodate its surface to many different grasping objects), thus having many advantages compared with existing grippers. The improvement of performance of both gripper fingers is compared regarding the adaptability and the stroke. It is shown that for the same actuator stroke the gripper finger with polynomial flexure hinges can realize better adaptability than the one with the beam elements.

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