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ADAPTIVE COMPLIANT GRIPPER FINGER WITH EMBEDDED EXTENDING ACTUATORS

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ABSTRACT

Developing a gripper that can grasp objects of widely varying shapes represents a challenging task. Compliant mechanisms with embedded actuators are one way to obtain the gripper which could accommodate its grasping surface to any irregular and sensitive grasping object. This paper presents the new solution of adaptive compliant gripper finger with embedded actuators. Embedded actuators (within gripper finger structure) are able to morph shape of the grasping surface to accommodate different objects. Novel approach to the synthesis of compliant mechanisms with embedded actuators is also presented. The main contribution of this approach is that optimization of the actuator placement is included in the design process. It will be shown that gripper finger can achieve many complex grasping patterns via embedded actuators (in this paper via extending actuators).

Index Terms - Adaptive gripper finger, compliant mechanism, embedded extending actuators, shape morphing surface, synthesis

1. INTRODUCTION

Developing a gripper that can grasp irregular and unpredictably shaped objects represents a challenging task. Grasping objects of widely varying shapes and surfaces essentially requires adaptability for safe and reliable gripping performance especially when fragile objects of different stiffness are manipulated. Much research has therefore been done to develop universal flexible grippers [1-7].

A flexible gripper design based on the use of compliant materials and internal pressure was introduced in [1]. This type of grippers conforms to the shape of an object by means of elastic gripping elements and pressurization. In [2] compliance is added in a selective compliant assembly robot arm (SCARA) in the form of a two ionic polymer metal composite (IPMC) fingers based micro gripper. Paper [3] presented adaptive gripping device called the “Buckling gripper”. The key design principle of the Buckling gripper is inspired by a caterpillar’s proleg that highly deforms depending on the shape of the contact surface. This key principle is applied to the gripper via flexural buckling. In [4] soft cable-driven gripper was introduced, featuring no stiff sections gripper is able to adapt to a wide range of objects due to its entirely soft structure. Paper [5] presented soft tentacles based on micropneumatic networks spatially distributed at the interface of two different elastomers. These composite elastomeric structures enable complex 3D motion of the tentacles which was used to grip and manipulate objects with complex shapes. In [6] soft starfish gripper was introduced. The gripper was designed by using embedded pneumatic networks (Pneu-Nets) of channels in elastomers that inflate like balloons for actuation. By actuating the individual networks, the device could continuously change its shape from convex to concave and thus can grip different shaped objects. Further investigation led to a completely different approach to a universal gripper where individual fingers are replaced by a single mass of granular material that, when pressed onto a target object, flows around it and conforms to its shape [7]. Most of these grippers require external drive (compressed air or electrical motor) [1, 4-7] and assembling. Moreover, there is no unique synthesis methodology.

One way to achieve adaptability is to use compliant mechanisms [8]. A compliant mechanism can be defined as a single-piece flexible structure which uses elastic deformation to achieve force and motion transmission (compliant mechanisms deform smoothly as a whole) [8]. This unique feature of compliant mechanisms is very promising option for the successful realization of shape-adaptable structures and provides a novel means to morph structural shape. Compliant mechanisms that change their shapes through structural deformations offer many benefits: reduced complexity, no wear, ease of manufacture, no assembly, better scalability, better accuracy, etc. Furthermore, compliant mechanisms can overcome many disadvantages of different mechanical grippers since the entire shape morphing structure is viewed as a compliant mechanism.

Synthesis of compliant mechanisms has been well studied in the past [9, 10], but little attention has been directed to problems related to synthesis of compliant mechanisms for shape morphing applications [11-13]. Synthesis methods developed in [11-13] 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. These methods cannot be applied when developing a gripper that can adapt to unpredictably shaped objects. 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, shape morphing gripper structures should be adaptive and should have a controllable response with exceptional manipulability.

This paper recasts the shape-changing problem as the challenge of how to design an adaptive compliant gripper that is controllable and capable of achieving multiple shapes. One such adaptive gripper could be formed as compliant mechanism with inherent actuators and sensors (Fig. 1). By embedding actuators and sensors within the compliant mechanism structure, gripper would be able to realize both sensing (via sensors) and appropriate response (via actuators and internal structure) to the unknown external environment, thus making the gripper adaptive. Such gripper is biologically inspired and holds the potential to lead to tightly integrated, highly functional, multi-purpose, adaptive system.

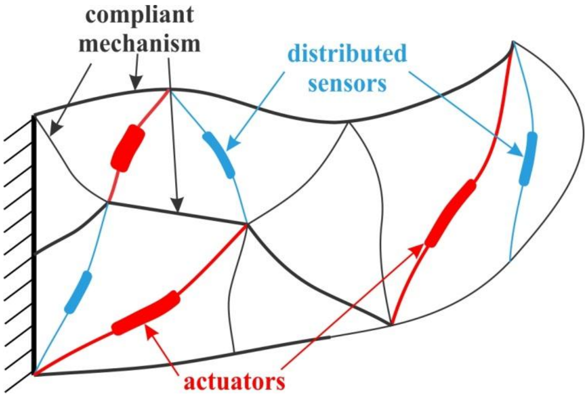

Fig. 1. Conceptual design of a compliant mechanism with embedded actuators and sensors

In this paper we pay more attention to the problem of embedding actuators since the primary goal of the paper is to develop gripper that is capable of achieving multiple grasping patterns i.e. to develop gripper that have structural adaptability. By embedding actuators within a compliant gripper structure, gripper may be capable of producing many complex deformations of the grasping surface i.e. gripper would be adaptive.

The algorithmic framework for distributed actuation and sensing within a compliant active structure has been already developed in [14], 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, intersection between elements often increases complexity and stiffness of the structure which can significantly lower the system functionality.

This paper presents the new solution of adaptive compliant gripper (in this paper only one gripper finger) with embedded actuators. We also present an improved 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 [14]). This represents one novel approach to the synthesis of compliant systems. We will demonstrate that obtained adaptive compliant gripper with embedded actuators may be capable of achieving many different grasping patterns and thus having many advantages over existing grippers.

2. SYNTHESIS METHODOLOGY

To develop adaptive compliant gripper we use compliant mechanisms with distributed compliance [9], 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 [9, 10, 15]. 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). In this paper we pay attention to topology optimization.

The allowable space for the design in a topology optimization problem is called the design domain (Fig. 2a). The topology is defined by the distribution of material and void within the design domain or as the pattern of connectivity of elements in a structure (Fig. 2b). The continuum based approach focuses on the determination of the optimal topology (the best material connectivity in a compliant structure). The designer only needs to define the size of the design domain in which the mechanism should fit, location of the supports, input and output ports, size of applied loads (Fig. 2a) as well as properties of the material from which the mechanism should be produced. Then, through the topology optimization, the optimal structural form (optimal topology) of a compliant mechanism for a specified input force and output deflection requirements is automatically generated (Fig. 2b).

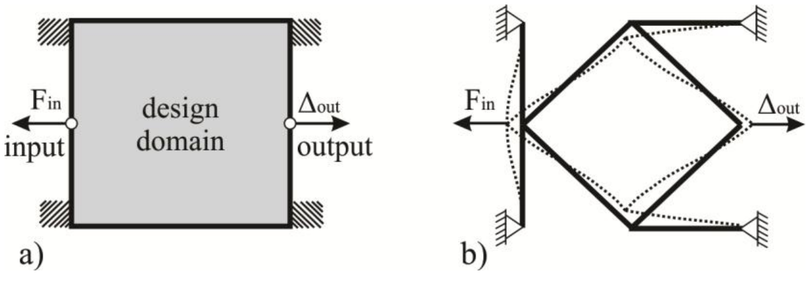

Fig. 2. Synthesis of compliant displacement inverter in which the input force F_{in} and the output displacement Δ_{out} are in opposite directions: a) design domain; b) optimal topology of compliant displacement inverter (deformed position is shown with dash lines) [16]

Adaptive compliant gripper could be seen as compliant mechanism with embedded actuators; embedded actuators would provide the gripper with ability to achieve multiple grasping patterns, thus making the gripper adaptive. In classical synthesis approach, actuators are added after a compliant mechanism is already developed, where determination of actuator placement is occurring outside the optimization process at the designer's option. In the literature the synthesis of single-actuator mechanisms has mainly been considered [9-13]. To develop an adaptive gripper, the structural topology of a compliant mechanism and actuator placement must be simultaneously synthesized (actuator type, orientation, size and location must be integrated as variables in the design process). Here actuator placement affects the structural topology of a mechanism and vice versa. Moreover, multiple actuators must be used. When multiple actuators are used, the question of control of such system must be considered. Incorporating control during the optimization process can enhance the controllability of an adaptive system. Central to this method is the concept of structural orthogonality, which refers to the unique system response for each actuator it contains [14]. These concepts (controllability and structural orthogonality) represent the structural adaptability of the system and are explored in detail in [14].

In [15] we have developed computer-coded algorithm for synthesis of compliant mechanisms with distributed compliance, and improved the topology optimization technique in [16]. 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.

The outline of the methodology that we use for developing adaptive compliant gripper with embedded actuators is shown in a pictorial example (Fig. 3). First the problem specifications are defined only for one gripper finger (Fig. 3a and Table 1). These includes: size of the design domain, 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.

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_{el}=2.48 GPa
actuator modulus	E_{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

Next the design domain is parameterized (Fig. 3b). The physical design space must be broken down so as to be represented by a set of variables that an optimizer can act on. Since we use compliant mechanisms with distributed compliance [16], the Grounded Structure Approach (GSA) [9, 10, 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 in a given structure; 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 [14], 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. 3b) 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 [16] is defined as well (Table 1).

When using the partially connected ground structure the solutions with intersecting elements are obtained [9, 15] where elements and actuators would intersect also [14]. 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 [14] so that the intersections between elements as well as actuators would be eliminated in the process of optimization. We apply the same ide as in [16], 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 [14]) 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. 3a). Thus, the number of actuators is held constant during the optimization, rather than minimized. To achieve a desired goal in the process of optimization, an objective function is needed. The objective function we used for the synthesis of the adaptive compliant gripper with embedded actuators is:

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

where: η_C is controllability [14], w_1, w_2, w_3 and w_4 are relative weighting constants, $d^{act}_{\text{min,target}} = 1\,\text{mm}$ is the minimum value of the output deflection, d^{act}_{min} is the displacement of the output points [14], d^{ext}_{max} is the displacement of the output points caused by external loading (the external load is applied at all three output points, all at once) [14], L_t is total element length, L_{target}=721.1 mm is the desired total element length [14] and n_{int} represent the total number of intersections in the structure [16].

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) [17] 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. 3b). Figure 3c shows the result for the best of population of 210 over 1000 generations. 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 (η_C=97.57%) of a compliant system is achieved. The results demonstrate that all the constraints are satisfied as well. Unlike solutions in [14] here the compliant system without intersections is obtained (Fig. 3c). This means that totally 1664 intersections are eliminated in the process of optimization.

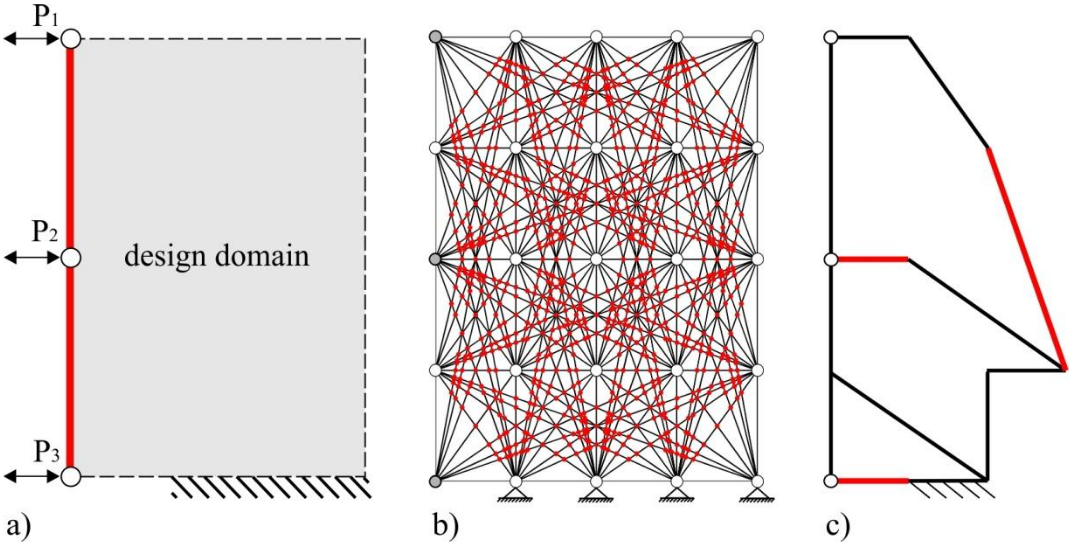

Fig. 3. The steps in the synthesis methodology: a) problem specifications; b) parameterization (intersections between elements are indicated by red dots); c) optimized topology of adaptive compliant gripper finger with embedded actuators (actuators are indicated by red lines)

3. FEM ANALYSIS OF THE ADAPTIVE COMPLIANT GRIPPER FINGER WITH EMBEDDED ACTUATORS

Based on the obtained solution (Fig. 3c) 3D solid model of the adaptive compliant gripper finger with embedded actuators was designed (Fig. 4a). 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. 4a). 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.

To investigate adaptability of the compliant gripper finger to different shapes of the gripping objects FEM simulations were performed (ABAQUS software was used). As boundary condition fixed support was applied at immobile part of the gripper finger (Fig. 4a). To simulate the extension of the actuators, as input a displacement of ±5 mm (stroke of actuator) in the direction of the actuators axis was introduced at the both ends of the all actuators (Fig. 4a). In this paper we simulate actuators that extend, but contraction actuators could be simulated as well. To show the capability of the gripper finger to produce multiple shapes of its shape morphing surface the FEM simulations were performed without any grasping object. Fig. 4 shows the results when extending actuators are used.

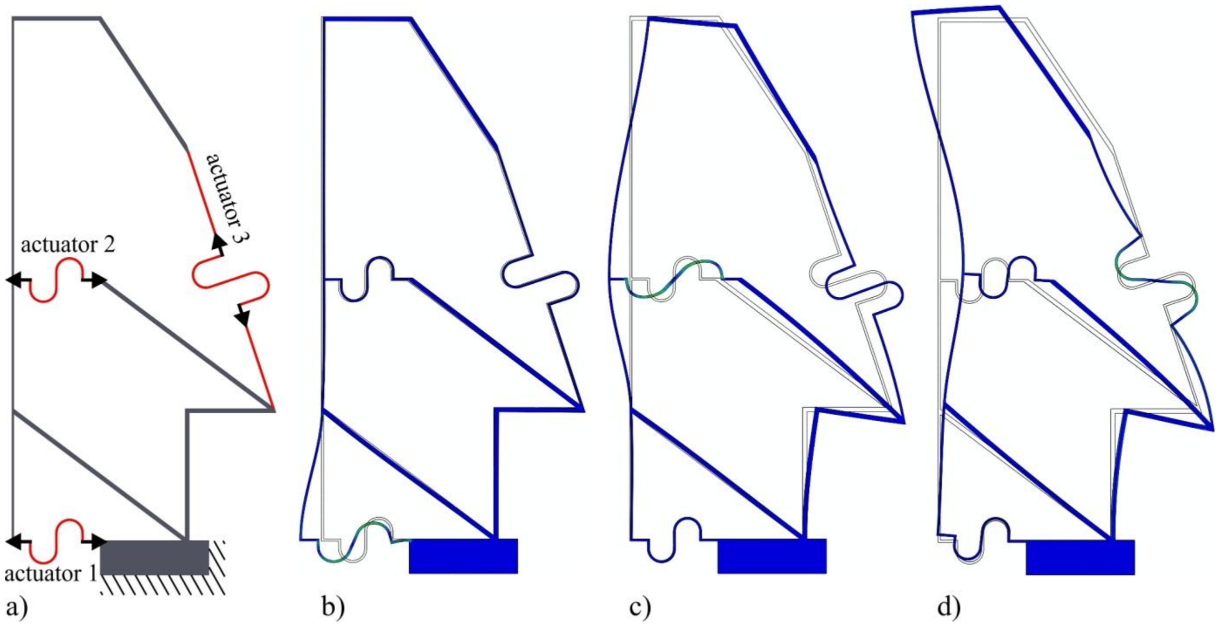

Fig. 4. Design of adaptive compliant gripper finger with embedded extending actuators (a) and FEM results when actuator 1 (b), actuator 2 (c) and actuator 3 (d) is active

The FEM results show that two main grasping patterns could be created: 'concave' (Fig. 4c) and 'convex' patterns (Fig. 4d); when actuator 2 is active an object of concave shape could be grasped (Fig. 4c), and when actuator 3 is active an object of convex shape could be grasped (Fig. 4d). Also actuator 1 could be used to accommodate the grasping surface of the gripper finger to different irregular shapes of the grasping object. Different grasping patterns could be achieved with different combinations of active actuators (Fig. 5). The results (Fig. 5) show that gripper finger has capability to grasp objects of different shapes and sizes, for example when using combination of actuator 1 and actuator 2 convex-concave objects could be grasped (Fig. 5a).

For different stroke of actuators, objects of different size could be grasped. For example, when actuator 3 is active (Fig. 4d) for different stroke of actuator (1 mm, 2 mm, …) convex objects of different radius could be grasped (Fig. 6). This is also the case when actuators 1 and 2 are active and with different combinations of active actuators.

In the design of the gripper finger presented in this paper, actuators with stroke larger than 5 mm (at both ends) could be used; the stroke is limited by the space in which actuator should fit. Actuator 1 and 2 could have the stroke of up to 10 mm (at both ends) and actuator 3, up to 60 mm.

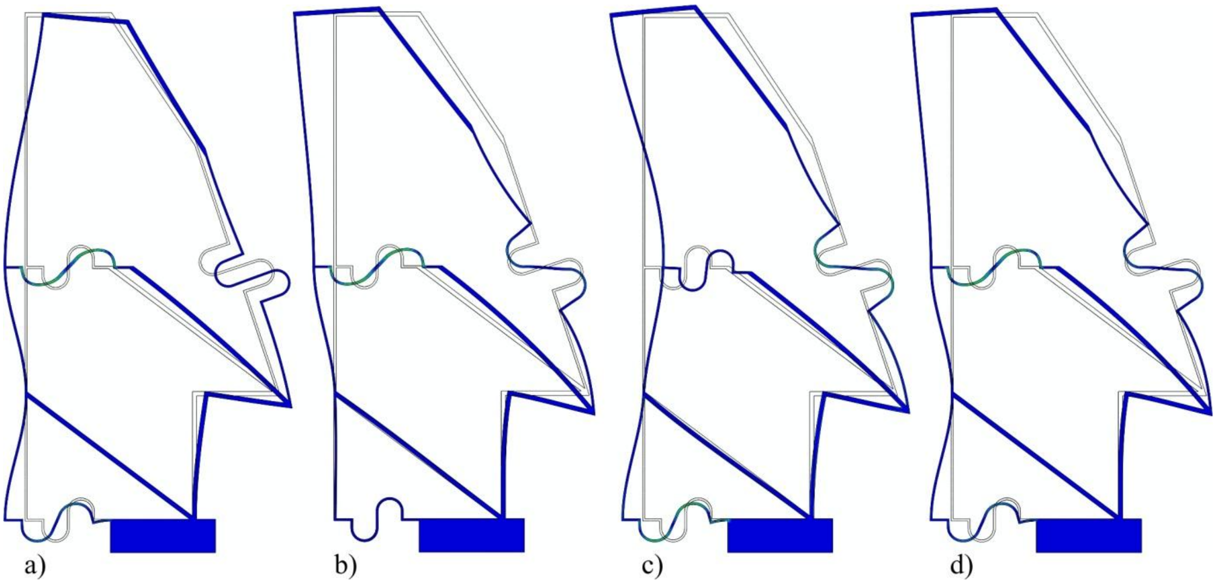

Fig. 5. FEM results for combination of different active actuators: a) actuators 1 and 2; b) actuators 2 and 3; c) actuators 1 and 3; d) actuators 1, 2 and 3

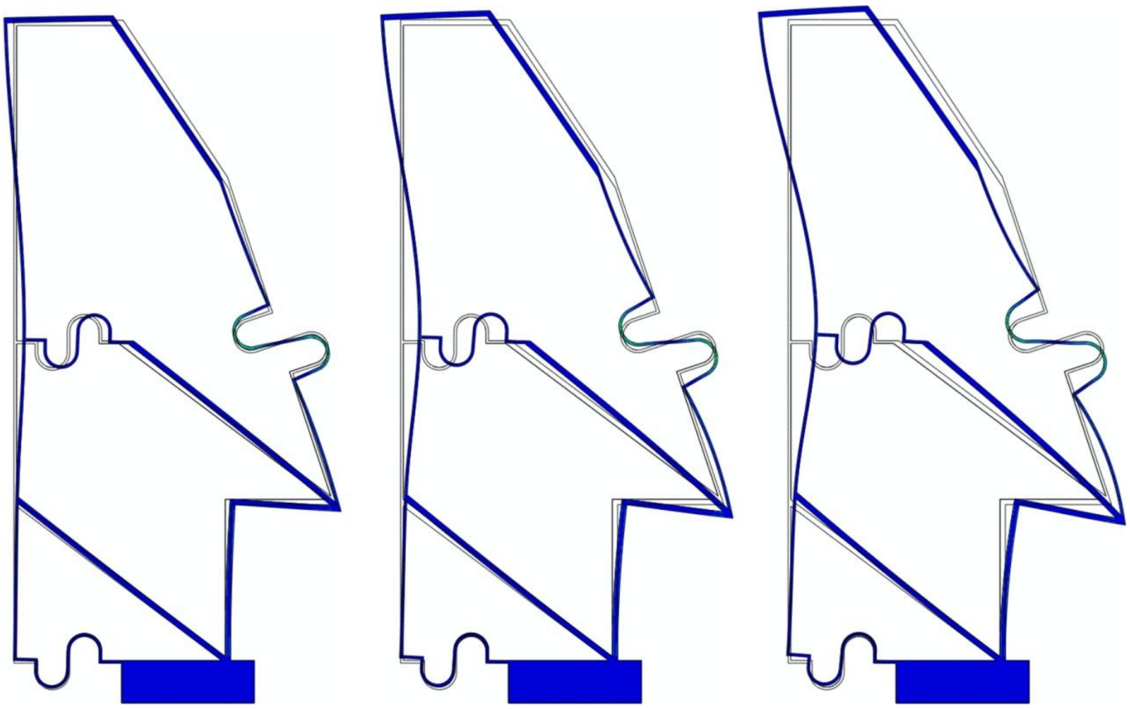

Fig. 6. Objects of different radius that could be grasped when actuator 3 is active

To verify the FEM results, physical prototype of the adaptive compliant gripper finger was made (Fig. 7). The gripper finger model was made from HDPE plastic (high density polyethylene E=0.5 GPa) throughout milling process using the CNC machine. The same as in simulations instead of embedding real actuators we used thin elastic elements (in form of a spring). Figure 7 shows the produced gripper finger. The adaptable behavior of produced gripper finger is in good agreement with the results obtained by FEM analysis.

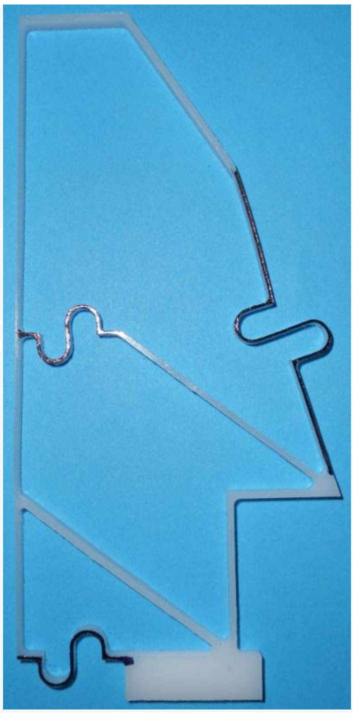

Fig. 7. Produced gripper finger

4. CONCLUSIONS

This paper presents the adaptive compliant gripper finger which has capability to adapt to different grasping objects via embedded actuators. With the introduction of multiple, optimally placed actuators our work focuses on developing gripper that has ability to achieve any shape required of the gripper.

The synthesis of compliant mechanism and actuators in one system is the main contribution in developing adaptive robotic gripper finger that can achieve unknown target shape changes. We improved the existing design methodology for simultaneous synthesis of compliant mechanism and actuator placement so that compliant systems without intersecting elements were obtained. This represents one novel approach to synthesis of adaptive compliant systems.

The FEM results demonstrate that by embedding actuators within the gripper finger structure the developed adaptive compliant finger has ability to produce many complex grasping patterns (gripper finger can accommodate its surface to many different grasping objects), thus having many advantages over existing grippers. The physical prototype was manufactured and tested. The results are in good agreement with results obtained by FEM analysis.

The method for developing gripper finger utilized in this paper is new and original principle for achieving adaptive grasping. The main difference between design presented in this paper and previously established gripper lies in: gripper structure and embedded actuators as monolithic structure, simple manufacturing process, low cost and easy adaptation to any irregular object shape. It is possible to make this gripper finger in micro domain too. In general, the results indicate that the adaptive compliant robotic gripper finger developed in this paper is a good starting point for further development and investigation.

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