Development of Soft Robotic Gripper with Embedded Active Elements

Andrija Milojević, Žarko Ćojbašić, *Senior Member, IEEE,*
Miša Tomić and Heikki Handroos, *Member, IEEE*

***Abstract*—Developing a gripper that can realize grasping of objects of different shapes and sizes, as well as objects with different stiffness, represents a challenging task. Compliant (elastic) mechanisms with embedded actuators and sensors are one way to realize a gripper which could adapt its grasping surface to objects of a different shape, thus achieving safe grasping and manipulation. This paper presents a new concept of soft/adaptive two-finger robotic gripper with embedded active elements (actuators and sensors). By using embedded actuation gripper can actively morph the shape of its grasping surface and realize different grasping patterns. By using embedded sensing gripper can detect contact with objects and via appropriate controller decide how to change the shape of the grasping surface and adapt to different and unknow shaped objects. Novel design method for obtaining adaptive grippers is also presented. It is shown that robotic gripper can achieve different complex grasping patterns via embedded actuators i.e. via combination of contracting and extending actuators that realize different stroke.**

***Index Terms*—Robotic gripper, adaptability, compliant mechanisms, active elements**

I. INTRODUCTION

Today in robotic industry and many other industries there is an excessive need for grasping objects of different shape, size and stiffness. For safe and reliable manipulation of such variety of objects, adaptability is required. Thus, developing a gripper that can actively adapt to differently shaped/sized objects and realize their safe manipulation, represents a challenging task. Such gripper could change the shape of its grasping surface and adapt to the unknow and complex shaped objects. Many researches developed different kinds of soft grippers that can realize adaptability in some way [1-8]. Most of the previously developed adaptive/soft grippers [1-8] require external drive (compressed air or electrical motors), assembling, high operating voltages, and have limited scalability (cannot be scaled to micro-domain). Moreover, the development of adaptive/soft grippers is usually based on the designer experience and intuition. Thus, there is no unique and general synthesis methodology how to develop adaptive grippers. Beside that, most of the adaptive grippers are based on passive adaptability (the grasping surface cannot actively change the shape), thus imposing some limitations in the complexity of object shape to which they can adapt.

This paper presents different concept of the soft robotic gripper that can achieve active adaptability. One way to realize adaptive gripper is to use compliant mechanisms with embedded actuators and sensors. Unlike rigid-body based mechanism, a compliant mechanism [9-14] represents single-piece structure that use elastic deformation of its individual segments to realize motion and force transmission. Compliant mechanisms offer many advantages over rigid-body mechanism like: no need for assembling, possible miniaturization, no friction and wear, no need for lubrication, reduced complexity and easy manufacturing, high precision output motion, built in restoring force and low-cost. Moreover, compliant mechanisms deform smoothly as a whole thus offering one specific feature and advantage for realizing adaptability. By embedding active elements i.e. sensors and actuators within the compliant mechanism, it is possible to develop a gripper that can both sense its environment (detect contact with objects) and appropriately respond and adapt to the unknow external environment (via actuation and internal structure). Embedded actuators (within the compliant structure) could morph the shape of the gripper grasping surface, thus providing the gripper with ability to realize many complex grasping patterns. Embedded sensors could provide the needed information for the controller. By developing advanced control that is based on artificial neural networks (ANN) and fuzzy logic, such gripper could also learn from its mistakes (over time) or recognize different shapes of grasping object, which could lead to realization of “intelligent” gripper. Existing compliant based grippers have limited grasping capabilities, do not possess active adaptability, moreover actuators and sensors are not embedded and added after the compliant gripper structure is already formed.

In this paper, the concept of adaptive two-finger robotic gripper with embedded active elements is presented, where the whole gripper structure with actuators and sensors is formed in one synthesis step. Here, more attention is paid to embedding the actuators, as one of the aim of the paper is to

Andrija Milojević is with the School of Energy Systems, Department of Mechanical Engineering, Laboratory of Intelligent Machines, Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland, and Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, (e-mail: Andrija.Milojevic@lut.fi, andrija.milojevic@masfak.ni.ac.rs).

Žarko Ćojbašić is with the Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, (e-mail: zcojba@ni.ac.rs).

Miša Tomić is with the Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia, (e-mail: mishatomic@gmail.com).

Heikki Handroos is with the School of Energy Systems, Department of Mechanical Engineering, Laboratory of Intelligent Machines, Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland, (e-mail: heikki.handroos@lut.fi).

show gripper capability to realize structural adaptability. Synthesis methodology for the adaptive gripper is already presented in our previous papers [15, 16]. It was shown that the obtained solution of one finger of the gripper could realize different grasping patterns when only contracting and only extending actuators where used [16]. The paper [17] presented the grasping patterns that one finger gripper could realize when some combination of contracting and extending actuators was used. In the paper [18] the shape and size of the objects that could be grasped when actuators realized different stroke were presented. This paper presents the further analysis and results when the rest of combination of contracting and extending actuator are used while they realize different stroke. The concept of grasping different shaped and sized objects with two fingers is also shown.

II. THE SYNTHESIS METHOD

To develop soft/robotic gripper, compliant mechanisms are utilized here. As a synthesis method for the compliant mechanisms, usually the topology optimization approach is used [9-14], thus similar design method is adopted.

The soft/adaptive robotic gripper could be seen as compliant mechanism with embedded actuators. To optimally design adaptive robotic gripper that can actively morph its grasping surface, the structural topology of a compliant mechanism and actuator placement (type, location, orientation, size) must be simultaneously synthesized.

Fig. 1 shows the outline of the synthesis methodology that was used for development of the soft/adaptive robotic gripper with embedded actuators in this study. Detailed explanation regarding the synthesis methodology could be found in [15, 16], here only an overview is presented.

In the first step of the synthesis process, problem specifications are defined; here only for one gripper finger (Fig. 1a and Table 1), as based on one finger, two, three or multi-finger gripper could be later designed. The problem specifications include defining: dimensions of the design domain (width and height of the space in which the gripper structure should fit), grasping - shape morphing surface (vertical left boundary of the design domain is chosen) and number of output points to be controlled on the grasping surface (three points are selected to represent the output surface where horizontal direction is set to be the direction of the desired output deflection) [16], fixed supports - ground (the part of bottom horizontal boundary of the design domain), material property (Young modulus) from which the gripper structure should be produced and other constraints such as minimum desired value of the output deflection $d^{\text{act}}_{\text{min, target}}$ and total element length L_t which is equivalent to the volume constraint [16]. All the design parameters that are used for the synthesis of the adaptive robotic gripper are given in Table 1.

In the next step, the design domain is parameterized (Fig. 1b). The design space must be somehow represented by a set of design variables that can be optimized. Here, the Grounded Structure Approach (GSA) is used for the parameterization, as this represents a common parameterization method in the synthesis of compliant mechanisms [10-14]. Thus, the design domain is divided with a number of nodes, and a network of beam elements which connect these nodes. Such kind of ground structure (Fig. 1b) represent initial solution for the set synthesis problem (Fig. 1a). The thickness of each structural element represents a design variable. Elements with thickness value of zero are removed from the initial structure while the other values represent thickness values (Table 1) [16]. Additionally, for every actuator in the structure, there is one variable that marks the element selected to be actuator; this variable has a value between 1 and the total number of elements (Table 1). For the actuators linear model is adopted, where at the ends of the beams axial force, equal to the actuator block force [16], is applied. All the parameters that are used for the parameterization are given in Table 1 [16].

TABLE I
DESIGN SPECIFICATION FOR DEVELOPMENT OF THE SOFT/ADAPTIVE ROBOTIC GRIPPER WITH EMBEDDED ACTUATORS

Design parameters	
Design domain	120 mm x 80 mm
Grid size	5 x 5
Nodal connectivity	4
Number of elements	168
Element modulus	E_{el}=2.48 GPa
Actuator modulus	E_{act}=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, 1, 1.5 mm
Thickness of grasping surface	0.5 mm
Genetic algorithm parameters	
Initial population	200
Generations	1000
Selection function	Roulette
Crossover	95%
Mutation	9%
Elite count	2

To find the optimal solution of the adaptive robotic gripper i.e. compliant mechanism with embedded actuators, optimization is applied as a search method. The initial solution of the synthesis problem represents a broad design space with large number of elements and design variables, thus search algorithm is needed to find the optimal solution. In the synthesis of the soft robotic gripper – compliant mechanism with embedded actuators, the main goal of the optimization is to achieve maximal structural adaptability of a gripper system (maximize controllability [15, 16]) with minimal number of actuators in the structure, while meeting given constraints. By maximizing structural adaptability i.e.

controllability of a system, the robotic gripper will be able to actively morph its grasping surface and realize multiple grasping patterns, where the influence of the actuators on the output points (grasping surface) will not be redundant. To realize full control of the three output points, the minimal required number of the actuators in the system is three, thus the number of actuators is fixed prior to the optimization (Fig. 1a) [16]. The objective function that is used for the synthesis of the soft/adaptive robotic gripper with embedded actuators is given in [15].

Based on the previously described steps, computer-coded algorithm is built [15], that can automatically perform optimization and based on the initial parameters give optimal solution of the soft/adaptive gripper.

As an optimization method, the Genetic Algorithms (GA) [19, 20] were applied here. Discrete nature of the optimization problem, structural elements are ether on or off, actuator variables are discreet, motivate us to use discrete optimization methods, such as GA's. Moreover, GA's can very efficiently search large space of design variables and find the optimal solution. The genetic algorithm parameters used in the synthesis of the soft/adaptive robotic gripper are given in Table 1.

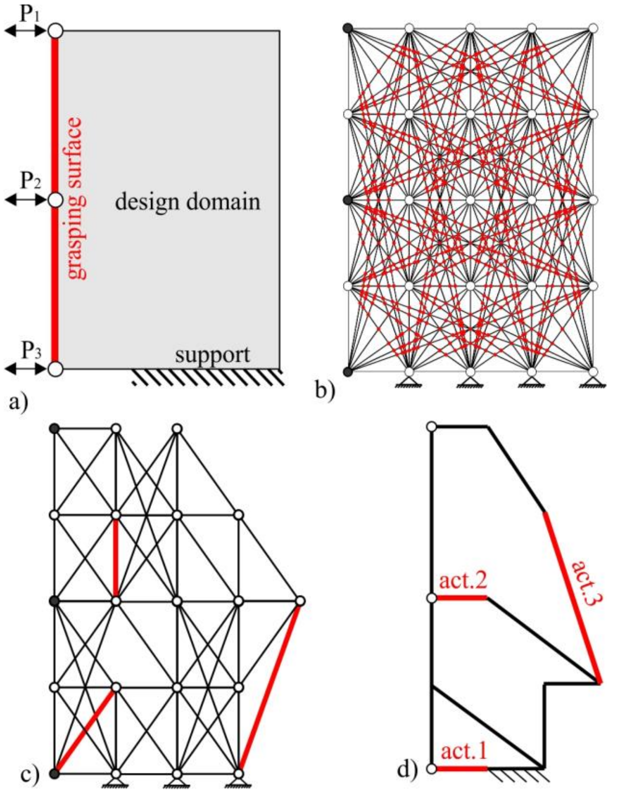

Fig. 1. Synthesis methodology for the soft/adaptive robotic gripper with embedded actuators: a) problem definition and specifications; b) parameterization of the design domain (intersections between elements are indicated by red dots); c) optimization process; d) optimized design (topology) of the soft/adaptive robotic gripper finger with embedded actuators (actuators are indicated by red lines) [15].

To obtain the optimal solution of the adaptive robotic gripper with embedded actuators more than twenty GA's were run. The optimization process starts with 168 beam variables in the initial ground structure (Fig. 1b). The optimal solution is obtained by simultaneously eliminating the structural elements from the initial ground structure and placing the actuators in the structure (Fig. 1c). This process is repeated until the solution that best satisfies objective function is found. The obtained optimal solution of the soft/adaptive robotic gripper with embedded actuators is shown in Fig. 1d. The results of optimization also show that the high controllability (η_C = 97.57 %) of a gripper system is achieved.

III. NONLINEAR FINITE ELEMENT ANALYSIS OF THE ADAPTIVE ROBOTIC GRIPPER WITH EMBEDDED CONTRACTING AND EXTENDING ACTUATORS

By using the obtained solution with optimization (Fig. 1c) 3D model of the soft/adaptive robotic gripper with embedded actuators was designed (Fig. 2a). Here the actuators were modelled as thin elastic elements (in a form of a leaf springs) that allow the actuation (Fig. 2a). Fig. 2 shows the concept of two-finger gripper where the gripper fingers could realize translation or rotation (this will be explored in some of the future work).

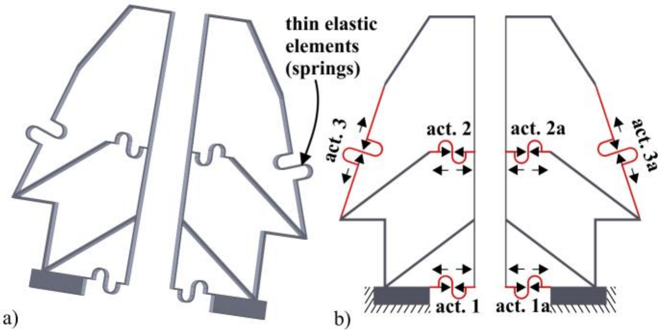

Fig. 2. A concept of soft/adaptive two-finger robotic gripper with embedded actuators: a) 3D model; b) FEM analysis set up (actuators are indicated by additional red lines).

To investigate the behaviour of the adaptive two-finger gripper i.e. to investigate if the gripper can realize different grasping patterns and thus adapt to different shaped objects, nonlinear finite element method (FEM) simulations were performed. In order to simulate the contraction and extension of the actuators, as an input for FEM, a displacement of ±4 mm (stroke of the actuator) was introduced at the both ends of the all actuators, in the direction of the actuators axis (Fig. 2a). Additionally, the gripper fingers were fixed at the bottom part (Fig. 2b). The results of FEM simulations of the one finger gripper behaviour with only contracting and only extending actuators were presented in [15]. In the paper [17] we simulated the case when combination of contracting and extending actuators are used. But in these papers [15, 17], only the results when actuators realize full stroke were presented. For a different stroke of the actuators, the adaptive robotic gripper could realize grasping of objects of a different size. The shapes and sizes of the objects that could be grasped when only contracting and only extending actuators realize different stroke, are presented in [18].

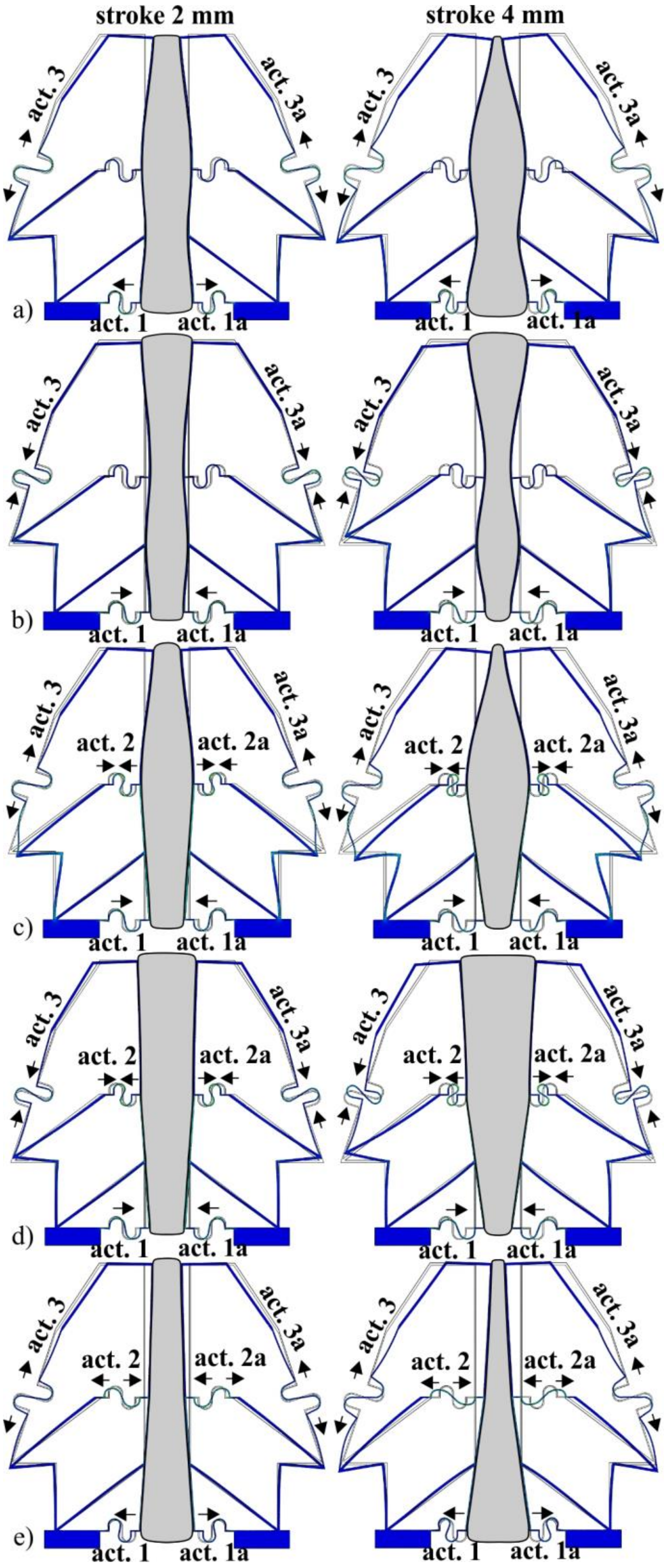

Fig. 3. Results of FEM simulations and shape of objects that could be grasped when different actuators are active and realize different stroke (2 mm and 4 mm): a) actuators1, 1a (contracting) and 3, 3a (extending); b) act. 1, 1a (extending) and 3, 3a (contracting); c) act. 1, 1a (extending), 2, 2a (contracting) and 3, 3a (extending); d) act. 1, 1a (extending), 2, 2a (contracting) and 3, 3a (contracting); e) act. 1, 1a (contracting), 2, 2a (extending) and 3, 3a (extending).

Fig. 3 shows the results of FEM simulations when different combinations of contracting and extending actuators are used, while they realize different stroke (2 mm and 4 mm on both ends of the actuators); concept of two finger grippers grasping objects of different shapes and size is shown.

The FEM results show that the adaptive two-finger gripper could realize grasping of differently shaped and sized objects, when different types of actuators are active (contracting and extending). Three commonly shaped objects could be grasped: convex-concave objects (when contracting 1, 1a and extending 3, 3a actuators are active, Fig. 3a), concave-convex objects (when extending 1, 1a and contracting 3, 3a actuators are active, Fig. 3b) and convex objects (when extending 1, 1a, contracting 2, 2a and extending 3, 3a actuators are active, Fig. 3c). Also, objects of different shapes and sizes could be grasped when other combination of contracting and extending actuators are used, as shown in Fig. 3d and Fig. 3e. The FEM results also show that with different stroke of the actuators (2 mm and 4 mm) convex-concave, concave-convex and convex objects of different radii i.e. different size could be grasped.

Much larger variety of objects could be grasped if one finger of the gripper uses one combination of the contracting and extending actuators while the other finger of the gripper uses some different combination of the active actuators. Moreover, it is possible that one finger uses only contracting while the other fingers use only extending actuators and vice versa. Beside this, many differently shaped and sized objects could be grasped if actuators in one finger of the gripper realize stroke that is different than the actuators stroke in the other finger.

Physical porotype of the soft/adaptive two-finger robotic gripper concept was manufactured from plastic by using CNC milling machine (Fig. 4).

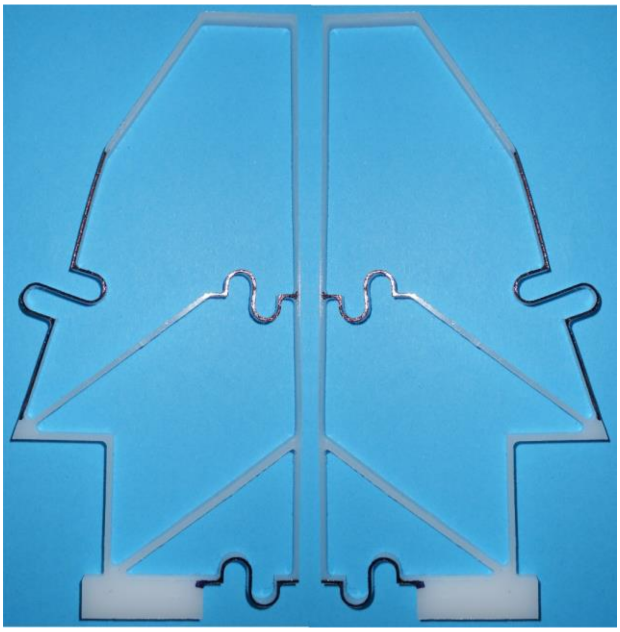

Fig. 4. Physical prototype of soft/adaptive two-finger robotic gripper concept, maid from plastic

IV. CONCLUSION

This paper presents the novel soft/adaptive robotic gripper with embedded active elements i.e. with embedded contracting and extending actuators. It has been shown that the presented gripper has capability to adapt to differently shaped and sized objects. The synthesis methodology for the adaptive gripper finger has also been presented. The introduced methodology represents one novel approach to development of adaptive grippers that can achieve active adaptability. The FEM simulations were performed and the results show that by using different combinations of active contracting and extending actuators, the two-finger gripper has ability to realize grasping of differently shaped objects. The results also show that with different stroke of the actuators, gripper could realize grasping of objects of different sizes. For the developed soft gripper both sensor and actuators are needed. Sensors in form of artificial skin are suitable. Sensors could be placed along the whole grasping surface in order for gripper to detect contact with object. As actuators, smart material based actuators are suitable. These options will be explored in some of the future research.

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