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Design of a Compliant Robot Hand by Structural Topology Optimization

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Abstract— **Safety and a soft touch are important for human-friendly robots. The use of fully compliant mechanisms has great potential for producing cheap and reliable compliant robots. This paper presents the problem formulation of compliant finger and design of compliant robot hand with four fingers and a thumb. The automatic design of compliant finger is by a structural topology optimization approach using a genetic algorithm. One compliant hand has been designed, fabricated and experimental results are presented.** **Safety and a soft touch are important for human-friendly robots. The use of fully compliant mechanisms has great potential for producing cheap and reliable compliant robots. This paper presents the problem formulation of compliant finger and design of compliant robot hand with four fingers and a thumb. The automatic design of compliant finger is by a structural topology optimization approach using a genetic algorithm. One compliant hand has been designed, fabricated and experimental results are presented.**

I. Introduction

Human hand can handle complicated tasks and developing an artificial hand with the capabilities of human hand has always intrigued mankind, and is still one of the big challenges of robotics. Controzzi et al. [1] reviewed artificial hands developed in prosthetics and humanoid robotics. Most of these dexterous hands are built from rigid materials, and have a complicated control system and a high number of degrees of freedom, but can only display compliant behaviour to a certain extent by applying algorithms such as compliance controls. Conventional designs of robotic hands focused on load capacity and position accuracy. Because of this, the robot hands developed so far are mostly based on methods of kinematic design and analysis. It is noted that position accuracy and load capacity are not very important in some cases, but safety and a soft touch should be addressed. The hands created so far still can not accomplish what common people do, such as interacting with humans naturally and safely or working in unconstructed environments. Partly, this problem can be solved by soft robots built of soft materials [2], [3], which are expected to be capable to do comprehensive tasks like grasping a large variety of objects.

An approach mimicking the human hand model is based on pseudo-rigid-body flexible mechanisms and abandons design concepts with exoskeletal structures, previously used by most of the developed robot hands. This approach is a promising way to the design of new type of robotic hands. Flexible mechanisms are compliant structures that deliver a desired motion or force by elastic deformation, unlike the rigid body motions of traditional mechanisms [4]. Concerning in particular its simplicity, mechanical structures inspired by biological models may contribute to the progression and success of the design, but application of compliant mechanism to robotic end-effector design has been predominantly limited to micro/meso-scale manipulation grippers [5], [6], [7]. Pseudo-rigid-body compliant hand can successfully grasp object despite location errors. University of Bologna Hand(UB Hand) [8] addressed the development of a novel humanoid robot hand, which is based on a mechanical architecture adopting deformable elements as joint hinges and modelled by the conventional kinematic synthesis methods. The SDM Hand(Shape Deposition Manufactured Hand) [9] is molded from polyurethanes. The molding process allows for the easy and low-cost mass production, and can incorporate embedded sensors. The SDM Hand is rigid for a stiff and stable grasp when actuated, while it is compliant with small contacting forces when unactuated, maximizing conformability. Carrozza et al. [10] attempted a compliant hand whose structure (both palm and fingers) is fabricated as a single part with flexible joints and tendon for adaptive grasp. Zisimatos et al. [11] proposed a series of compliant, modular robot hands which can be easily reproduced. Zhou et al. [12] presented a compliant gripper whose finger using soft-rigid-hybrid structures, combining rigid joints with soft fiber-reinforced pneumatic actuators. Our previous paper [13] presented a prosthetic hand using flexure hinges. The hand has 4 degree of freedoms and compact structure with 5 fingers whose joints are with helical springs and coupled by tendons.

The use of fully compliant mechanisms is promising for producing cheap and reliable compliant robots [14]. Suzumori [15] used a pneumatic soft actuator to implement the robot compliance. It mainly consists of a pneumatic power system and a fiber-reinforced rubber body. The actuator is flexible, but it needs a bulky power system. Katzschmann et al. [16] developed a soft gripper - the DRL Soft Hand which can grasp a set of objects of different size, shape, and compliance and identify them [17]. Deimel and Brock [18] developed the RBO Hand 2, an cheap and highly flexible multi-fingered hand actuated by inflating airfilled chambers. Gupta et al. [19] described an approach used to train it to perform dexterous manipulation tasks.

In the previous studies, the bio-inspired design and concept design have received great success to develop compliant/soft hands. Structural topology optimization approach [20] can provide an alternative way to generate fully compliant mechanisms only based on input-output requirements. The basic idea is to treat

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the design problem as a structural optimization problem where the optimized continuum structure can satisfy the mechanism requirements and, thus, it is also called topology optimization of compliant mechanisms [21], [22], [23], [24]. Being monolithic and continuous, compliant mechanisms present a design challenge - the 'best' shape and topology of a solid structure should be found whose elastic deformation would perform a behavior like a conventional linkage mechanism. Suitable structural representation schemes, problem formulation, performance analysis, and optimization are required, which are totally different from the kinematic analysis of rigid-body mechanisms. This research addresses the design problem of a fully compliant robot hand by structural topology optimization. The structural design problem formulation of compliant fingers is described in Sec. II. The genetic algorithm used for topology optimization is briefly outlined in Sec. III. The design results are demonstrated in Sec. IV while some concluding remarks and possible future work are given in Sec. VI.

II. Problem Formulation

The design of a compliant finger is constrained in a design do- main shown in Fig. 1. An illustration of a compliant finger is given. The shape in solid lines represent the initial mechanism, and the dashed lines show its possible deformed shape due to the input load. Generally, a compliant robot hand finger refers to a compliant mechanism with load-bearing capacity. In order to extend its working space, an output path is preferred to be as long as possible when stresses are limited. The topology optimization synthesis of it can be formulated with flexibility and load performance objectives, and one stress constraint described in Secs. II-A - II-C to achieve the desired behavior.

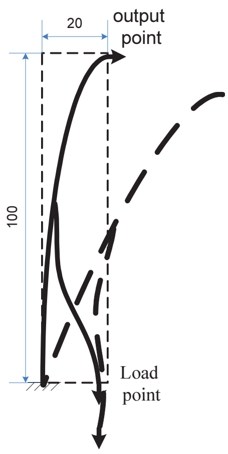

Fig. 1: Sketch of design domain and a finger

A. Flexibility Objective

Maximize deflection of the output point can be devised to maximum flexibility. When the input is a variable imposed, the ratio of the output deflection to the input displacement can be used to represent the motion transition efficiency of the mechanism. This ratio is called the geometric advantage. The initial state and the final state of the structure determine the geometric advantage objective (f_{GA}). Here, the undeformed shape of the mechanism is the initial state while the deformed shape under fully applied load is defined as the final state. If $\mathbf{r}_{out}$ and $\mathbf{r}_{in}$ denotes the position vectors of the output and input point, respectively, then the geometric advantage objective is determined by

$$\text{Minimize} \qquad f_{GA} = -\frac{\mathbf{r}_{out} \cdot \mathbf{u}_{out}}{\mathbf{r}_{in} \cdot \mathbf{u}_{in}} \tag{1}$$

where $\mathbf{u}_{out}$ is the unit vector perpendicular to the output boundary, and$\mathbf{u}_{in}$ is the unit vector perpendicular to the loading boundary.

B. Load Capacity Objective

The aim here is to maximize the load-bearing capacity. Mechanical advantage(MA) can be referred as the ratio of output to input force. The mechanical advantage objective (f_{MA}) is given by

$$f_{MA} = -\frac{F_{out}}{R} \tag{2}$$

where F_{out} is the reaction force at the output point and R is the resulting actuation force at the input port .

C. Stress Constraint

The aim here is to hinder fatigue or failure. A constraint on the maximum stress is crucial in the compliant mechanism synthesis. To obtain compliant and strong designs, stress failure conditions should be incorporated in topology optimization of compliant mechanism.

A stress constraint in a dimensionless form may be expressed as

$$g_{stress} = \frac{\sigma_{peak-von-Mises} - \sigma_y}{\sigma_y} \leq 0 \tag{3}$$

where σ_y is the yield strength of the used material and $\sigma_{peak-von-Mises}$ denotes the peak von Mises stress.

III. Multiobjective Genetic Algorithm

Topology in some sense is qualitative, and the topology changes are discrete. A genetic algorithm fits well to topology optimization problems as it is a evolutionary, flexible, and random-guided discrete search method. Additionally, because the genetic algorithm does not need any gradient information, genetic algorithm as derivative-free method can handle any complex or arbitrary objectives. Moreover, genetic algorithm searches among a population of solutions which is different from other search methods. This feature give it a more extensive search of the global optimal solution, and Pareto Front of the objective functions make it a powerful state-of-the-art approach for multi-objective optimization problems. Genetic algorithm can solve a common problem in gradient-based topology optimization of imposing local stress constraint on each cell. The approach used in this paper bases upon the genetic algorithm in T [25]. It provides a constraint handling strategy by separate nondomination Pareto ranking for constraints satisfaction and objectives. To formulate the chromosome code used by the genetic algorithm, a representation of mechanism with fat Bezier curve is designed for the compliant robot design. It can directly generate smooth boundary structures and a more detailed description of the representation scheme can be found in prior work [26], [27].

IV. Design Results

As to the material itself, a material with a high Sy/E ratio is helpful to achieve high strain without yielding. As shown in Table I, polypropylene and PTFE strongly support the use of the one-piece concept. The material used for the compliant finger is PTFE.

TABLE I

Material	E(Mpa)	S_y(Mpa)	Sy/Ex1000
PTFE	345	23	66.7
Nylon (type 6)	2620	81	30.9
Polyprolypene	1400	34	24.3
Aluminum	6900	95	13.8
Steel (Sandvik 11R15)	186000	1950	10.5
Titanium Alloy	105000	730	7.0

The optimization algorithm is realized through a C++ program. A finite element analysis gives the values of the constraint and objective functions for every design. A total of 501 generations was run for each optimization, and the population size per generation is 100. The best f_{GA} and the corresponding solution's f_{MA} versus generation number is plotted in Fig. 2. f_{GA} and f_{MA} values on the plot belong to the corresponding generation's non-dominated solution with the best geometric advantage objective. As until the fifth generation there is no feasible solution, the plot begins at that generation.

Fig. 3 shows plots of the best f_{MA} and the corresponding solution's f_{GA} versus generation number. The Pareto Front of the optimization problem in the final generation is shown in Fig. 4, where solid shape markers denote the feasible Pareto Front solutions. Three of the Pareto Front solutions at the final generations denoted by hollow diamond shapes in Fig. 4 are presented in Fig. 5. Fig. 5(a) presents the solution with best f_{GA}. Fig. 5(b) presents the solution with the best f_{MA}. Another solution in the Pareto Front is given in Fig. 5(c). It is an intermediate solution between the two extreme solutions in Fig. 5(a)of the best f_{GA} and Fig. 5(b) of best f_{MA}.

The solution with best geometric advantage objective (Fig. 5(b)) was obtained at the 444th generation, with f_{GA} of -5.77 and f_{MA} of -0.09. The input force for the loading case is 10.3 N. Fig. 6 shows a prototype for this finger by applying a drawing software to refine the design structures. The compliant finger was actuated to investigate the deformation, and the output port displacements were measured for comparison with the displacement resulted from the finite element analysis (Fig. 7) from the optimization run. The comparison is shown in Fig. 8. The actual experimentally measured displacements of the prototype are somehow different from the finite element computed displacements. One reason for it is maybe the refinement of the

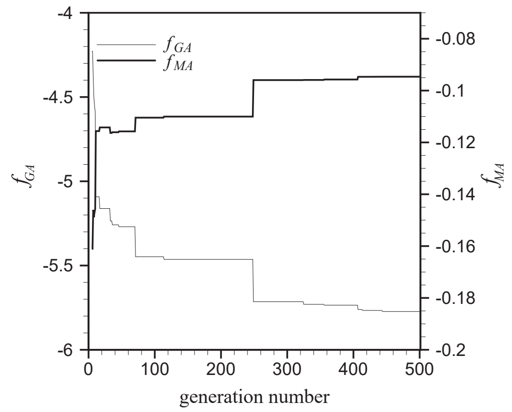

Fig. 2: History of the best geometric advantage objective (f_{GA}).

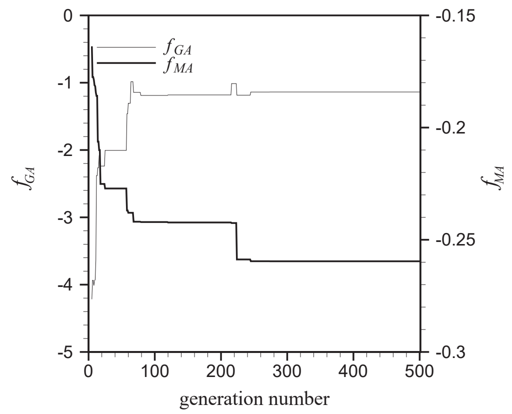

Fig. 3: History of the best mechanical advantage objective (f_{MA}).

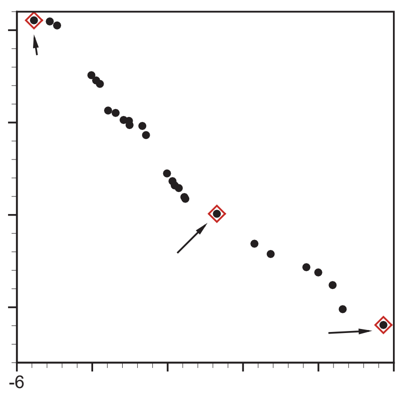

Fig. 4: Plot of non-dominated solutions at 501st generation.

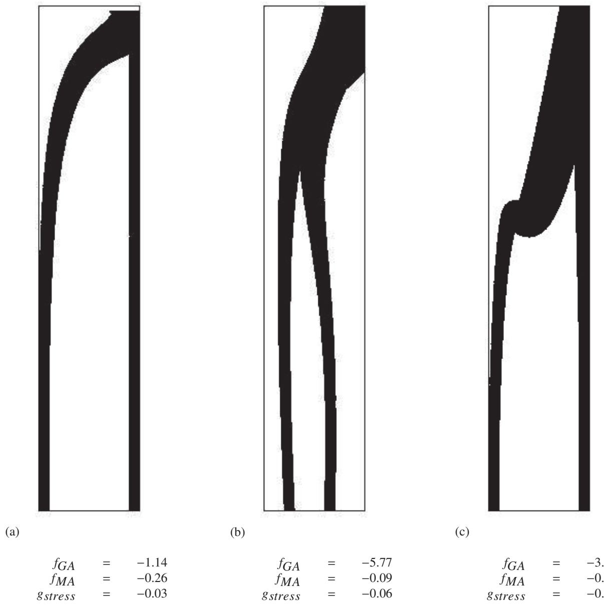

Fig. 5: Three Pareto Front solutions at 501st generation.

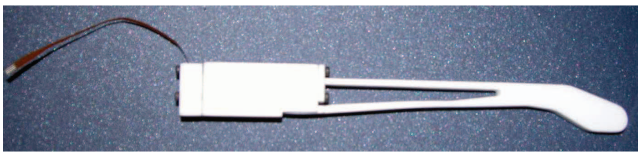

Fig. 6: Compliant finger prototype.

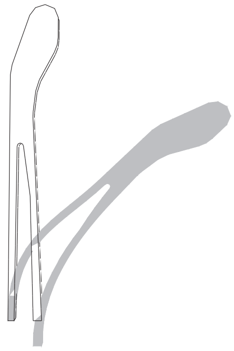

Fig. 7: The undeformed and deformed geometries of this solution.

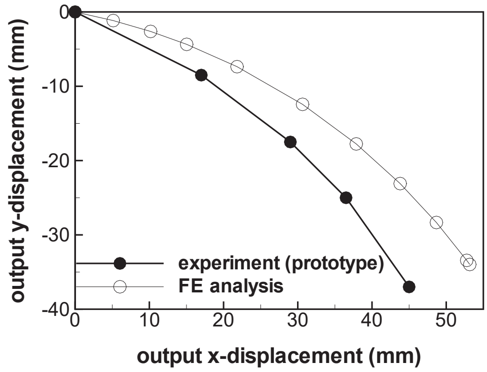

Fig. 8: the output path.

structure. The second possible reason is the accuracy of finite element analysis. However, even though the paths do not exactly match, the prototype can still be used to form the robot finger that has a large geometric advantage and a moderate mechanical advantage.

V. Experiments

Linear actuators(produced by Faulhaber) with integrated position sensor are used for the actuation. Because of their small size, they can be easily boxed into the forearm. The actuator performances are suitable to drive the fingers, as presented in Table II:

TABLE II

Max. speed	30mm/min
Nominal push force continuous operation	15.7N
Nominal push force intermittent operation	23.6N
Length with motor	22.8mm
Max. linear travel	12mm

The compliant hand, shown in Fig. 9, has four fingers and a thumb arranged in a human opposition arrangement. The five fingers form a completely self-contained unit. To achieve modularity, all the fingers are the same as shown in Fig 6. The prototype of the designed hand is shown in Fig. 10, whose size and shape are similar to the human hand. All actuators are integrated in the finger's base directly.

Seven prehensile hand gestures based on [28] were done as illustrated in Fig 11. The first column illustrates the seven hand gestures, and the last two columns show the corresponding CAD model and compliant hand when gasping objects. The main function of the cylindrical gestures is to grasp cylindrical objects, such as an ordinary cup. Hook gesture is used to carry some objects, such as a bag. Lateral gesture is to hold some flat subjects, such as a key. Point gesture is used to point a direction. Rest gesture is when there is no actuation. Tripod gesture is used to carry some small objects, and tip is to pinch some very small objects, such as a needle.

The overall experiment system is shown in Fig. 12. It consists of UDMlc motion driver, SPiiPlus NTM motion controller, and the matched software MMI Application Studio from ACS Motion Control company.

VI. CONCLUSIONS

Most of these dexterous hands are built from rigid materials, and have a complicated control system and a high number of degrees of freedom, but can only display compliant behaviour to a certain extent by applying algorithms such as compliance controls. And they are mostly based on methods of kinematic

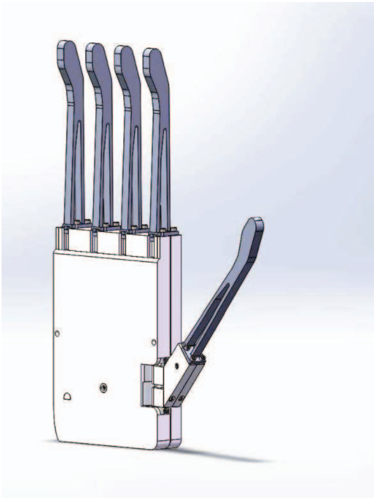

Fig. 9: CAD model of the compliant hand.

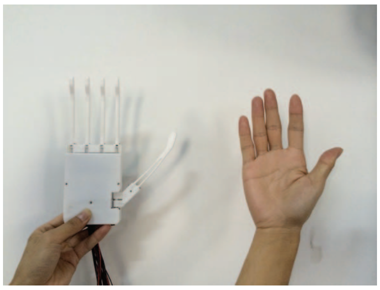

Fig. 10: The prototype of the prosthetic hand.

design and analysis, while a little research has applied fully compliant mechanism concept to robot mechanical design. In this work, fully compliant mechanisms has been used for producing compliant robot hand where safety, gentle motions, and a soft touch can be realized. As to the design, robotic hands from the 'compliant mechanism' concept shows good properties in terms of ease of manufacturing and assembly. Also, it is proven to be quite satisfactory in terms of kinematical behavior. And it is easy to host the distributed sensory equipments. The experimental tests showed that the fully compliant mechanism concept can be profitably introduced into the design of articulated robotic fingers. Future work will focus on going deep into general design criteria as well as the control problem of the compliant robot.

Acknowledgment

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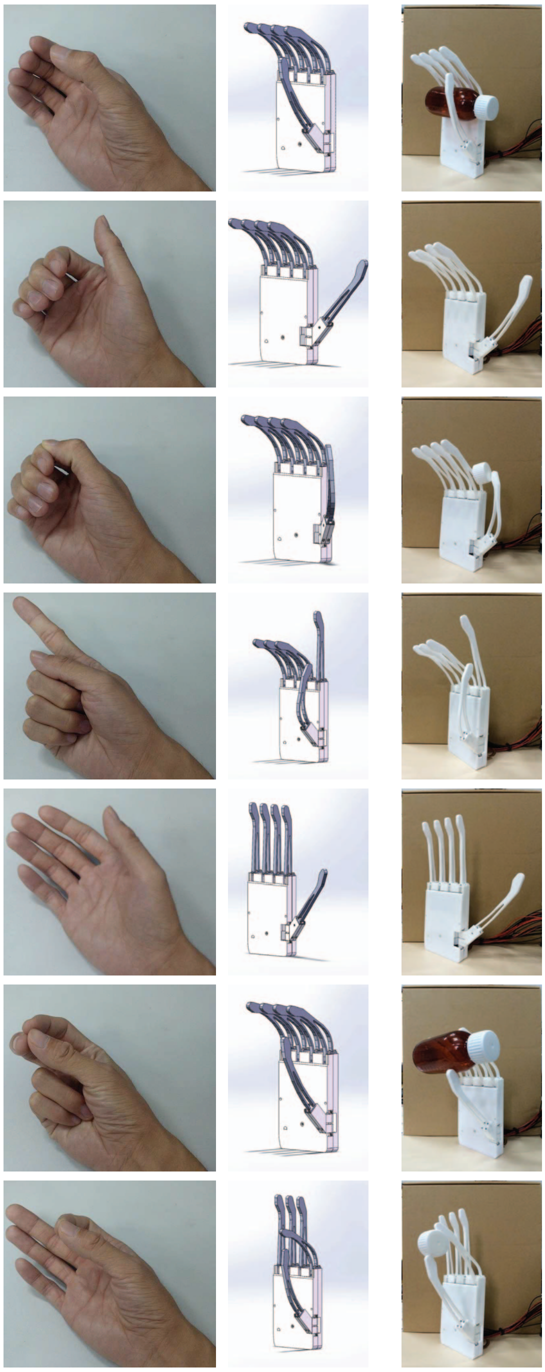

(a)
(b)
(c)
(d)
(e)
(f)
(g)

Fig. 11: Seven kinds of hand gestures.

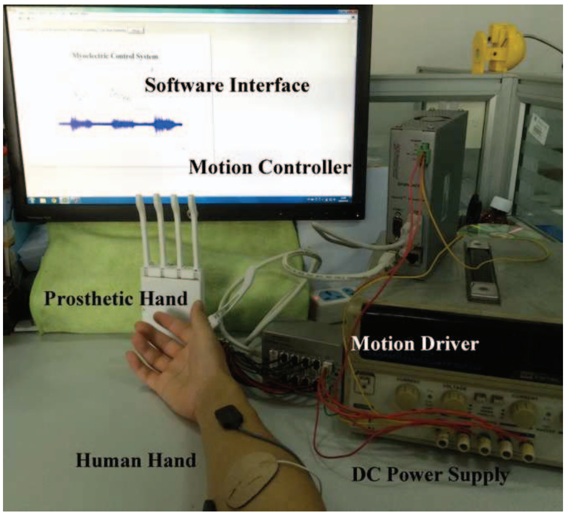

Fig. 12: The overall system.

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