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SOFTWARE FOR SYNTHESIS OF COMPLIANT MECHANISMS WITHOUT INTERSECTING ELEMENTS

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Abstract. *A compliant mechanism is defined as a single-piece structure that transfers motion or force through elastic deformation. The synthesis of this kind of mechanisms represents a challenging task, especially because their flexible segments usually must undergo large, nonlinear deflections which include a difficult nonlinear analysis. In this paper the new software for synthesis of compliant mechanisms is described. The software uses an improved topology optimization technique that is especially useful when the designer does not have a particular compliant mechanism already in mind. The intersection between the elements in the compliant mechanisms obtained by using the existing topology optimization technique often increases stiffness of the structure which needs to be flexible. The topology optimization technique is improved in the software so that compliant mechanisms without intersecting elements are obtained. The methodology that the software uses and its capability will be shown on the examples of the synthesis of a compliant gripper and a compliant displacement inverter.*

Key words: *Compliant Mechanism, Synthesis, Topology Optimization, Compliant Gripper, Compliant Displacement Inverter*

1. INTRODUCTION

A compliant mechanism can be defined as a single-piece flexible structure which uses elastic deformation to achieve force and motion transmission [1]. Compliant mechanisms differ from conventional rigid-link mechanisms in that they gain their mobility from the deflection of the flexible members, contain no pin joints and are intentionally flexible.

A compliant mechanism is a combination of a structure and a mechanism, since the jointless feature resembles a structure, while the function of the structure resembles a mechanism. Compliant mechanisms are designed to be flexible enough to transmit motions, yet stiff enough to withstand external loads. The transition from the conventional mechanism to the compliant

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one is shown in Fig. 1. The function of both the grippers is to transfer the input force to the output and to grasp an object. While the rigid-link gripper gains functionality by a rigid-body mechanism, the compliant one undergoes elastic deformations due to an input actuation.

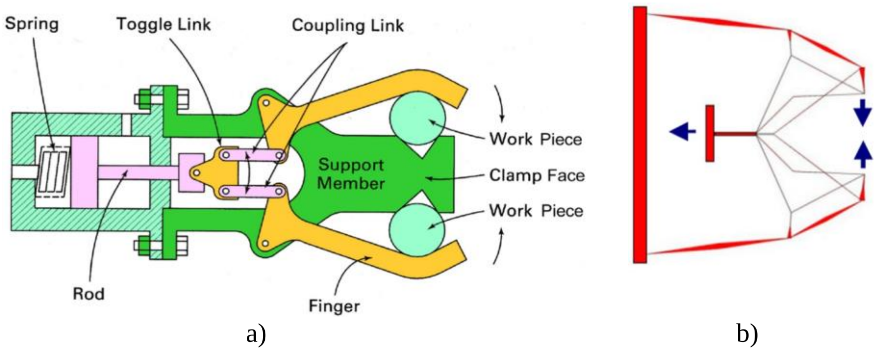


Fig. 1 a) Rigid-link gripper; b) compliant gripper [2]

The main advantages of compliant mechanisms over classical ones are: simplified manufacturing, reduced assembly costs, no wear, no backlash, reduced noise, easier maintenance, no need for lubrication, built-in restoring force, better scalability and accuracy. Because of these advantages compliant mechanisms are used in many applications including manufacturing, aerospace, robotics, biomedical devices, MEMS, grippers, motion amplifiers, positioning devices, adaptive structures, shape morphing structures, surgical tools, etc. (see e.g. [2], [3], [4]).

The compliant mechanism synthesis represents a challenging task and has been well studied in the past [5], [6]. The compliant mechanism synthesis is not so straightforward because the flexible segments usually must undergo large, nonlinear deflections, introducing high stresses and a difficult nonlinear analysis. A nonlinear analysis usually includes solving nonlinear differential equations for accurate prediction of flexible segments motion. To include the solutions to these equations in the design process would be tedious and overly complex, thus it is efficient and easy to use tools for compliant mechanism synthesis. Different methods are used for the optimal synthesis of compliant mechanisms [7], [8], [9], but more appropriate and more robust tools for the synthesis of compliant mechanisms for real-world applications are missing.

This paper presents a new software and a novel approach to the compliant mechanisms synthesis. The software uses a topology optimization technique that is especially useful when the designer does not have a particular compliant mechanism already in mind. The intersection between the elements in compliant mechanisms obtained by using the existing topology optimization technique often increases complexity and stiffness of the structure which can significantly lower the mechanism functionality. The topology optimization technique is improved in the novel developed software, so that compliant mechanisms without intersecting elements are obtained.

The software, its efficiency, functionality, capability and methodology will be shown on the example of the synthesis of a complaint gripper and a compliant displacement inverter which are common benchmarking problems that have been broadly studied [8],

[9]. The synthesis of the mechanisms (gripper and displacement inverter) with and without intersecting elements will be shown for comparison. The developed software intends to provide an easy-to-use tool for compliant mechanism design, which, we hope, will lead to novel solutions for today's engineering problems.

2. Synthesis of Compliant Mechanisms with Distributed Compliance

Compliant mechanisms can be subdivided into two groups: mechanisms with lumped compliance and mechanisms with distributed compliance [10], [11], [13]. Mechanisms with distributed compliance (Fig. 7, Fig. 9, Fig. 15) make use of longer and thicker bending elements. They gain their mobility through elastic deformation of flexible members and compliance is distributed more or less equally in the entire mechanism (i.e. they deform as a whole).

The continuum synthesis approach is used for the design of mechanisms with distributed compliance [5], [7], [9], [10]. The synthesis methodology used in the continuum based 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 more attention is paid to topology optimization, because this is a more difficult and "creative" part of the design process. The allowable space for the design in a topology optimization problem is called the design domain (Fig. 3). 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. 7, Fig. 9, Fig. 15). 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. 3) 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. 7, Fig. 9, Fig. 15).

3. New Software for Optimal Synthesis of Compliant Mechanisms

In the past many computer-coded algorithms and software for synthesis of compliant mechanisms have been developed [7], [9], [12], but most of them require some knowledge from the field of topology optimization. This has motivated us to develop a new tool for the synthesis of compliant mechanisms, that can be used by experts and designers who are not necessarily familiar with the details of topology optimization techniques. The software provides an interactive and automated design route to synthesize compliant mechanisms for any desired input-output force/displacement characteristics while meeting given constraints. The algorithm on which the software is built is shown in Fig. 2.

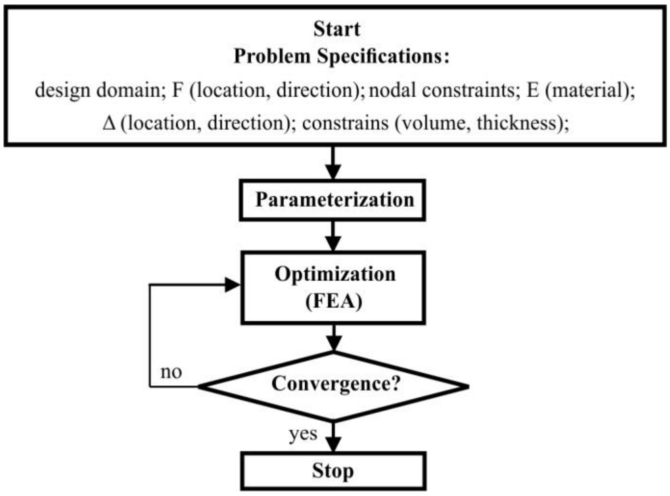


Fig. 2 Computational procedure

In the first step the problem specification is given by the user, including the size of the design domain, the input force (intensity, point and direction), the desired output deflection (size, location and direction), the material property (Young modulus) from which the mechanism should be built and other constraints (such as location of the fixed nodes).
In the second step the design domain is parameterized. 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 mechanisms with distributed compliance consist of individual flexible members, the Grounded Structure Approach (GSA) [7] is used for the parameterization. Since a compliant mechanism relies on elastic deformation (bending) of constituent elements, beam elements are used to generate the topology. Therefore, the prescribed design domain is divided into a number of nodes, and a network of beam elements connecting these nodes (Fig. 4) serves as an initial guess. The design variable is the thickness of each element. A thickness value of zero deactivates the element, removing it from the structure; other values represent thickness values. In the software, the thickness of each element can be one of three predetermined discrete values defined by the user. In the software the designer has the option of specifying the degree of nodal connectivity, that is, every node can be connected by an element to every other node in the grid, or only to nearby neighbors.

After the parameterization is done, in the third step, the optimization starts. Because of the broad design space and number of elements, topology synthesis problems are solved with optimization methods. When the parameterization is discrete (i.e. elements are either on or off), the discrete optimization methods are used. These methods include the field of evolutionary optimization, of which Genetic Algorithms [8] are applied here. Genetic Algorithms are a commonly used method in topology optimization of compliant mechanisms [2], [4], [7], and they have been well studied in the past. After the optimization procedure converges, some elements will be removed from the original exhaustive set. The remaining elements will define the topology for the compliant mechanism, which represents the optimal solution for the given problem; the optimized compliant mechanism is a network of a subset of beam elements (Fig. 6).

The capabilities of the developed software and its efficiency will be shown on the example of the synthesis of a compliant gripper and a compliant displacement inverter, which are common benchmarking problems in the topology optimization field [5], [12].

4. SYNTHESIS OF THE COMPLIANT GRIPPER AND THE DISPLACEMENT INVERTER

The goal is to design two compliant mechanisms: a compliant gripper and a compliant displacement inverter, by using the newly-developed software with the topology optimization technique that is commonly used for the synthesis of compliant mechanisms. In the first case we want to design a compliant gripper that can realize desired output motion Δ at the indicated location, when input load F is applied (Fig. 3a). This will allow the device to grip some object at the output point. In the case of the displacement inverter we want to design a compliant structure that can realize desired output displacement Δ in the opposite direction as input force F (Fig. 3b). The design domain for both cases in Fig. 3 represents the upper-half view, since this is assumed to be a symmetric problem without any loss of generality in the solution procedure.

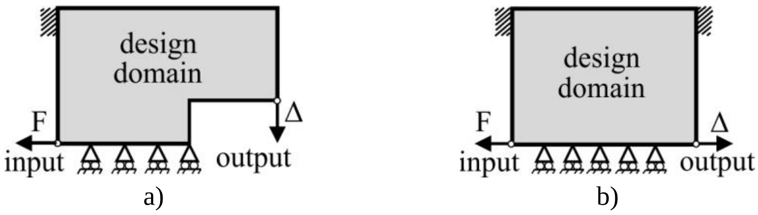


Fig. 3 Design domain and problem setup for synthesis of the compliant gripper (a) and the compliant displacement inverter (b)

4.1. Problem specification and parameterization

In the software, the size of the design domain, in which the mechanism should fit, must be defined first (only the rectangular design domain can be defined). Then, the user needs to input the desired number of nodes, creating n_l x n_h grid of nodes. This defines the resolution with which the design domain will be parameterized. After this, the software automatically parameterizes the design domain using the GSA. The design domain is broken down so that the grid of nodes is interconnected by beam elements (Fig. 4).

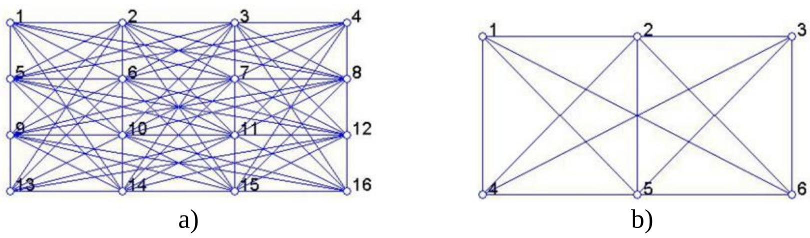


Fig. 4 Initial ground structure: a) compliant gripper; b) compliant displacement inverter

In the obtained ground structure all the nodes are initially interconnected i.e. the ground structure is "fully connected". A fully connected structure can lead to overlapping elements that are difficult to produce. Thus, certain filters are implemented in the software that eliminates the overlapping elements. This partially connected structure results in much fewer design variables and greatly reduced computation time, while still effectively representing the design domain. The user can also define the degree of nodal connectivity, that is, the number of nodes that one node can be interconnected maximally in the directions of the width and the height of the design domain (how many fields one beam element can cross). This can significantly reduce the grid resolution of the ground structure which can speed up the process of optimization. For the case of the compliant gripper and the compliant displacement inverter, design specifications of the design domain, size of grid nodes and degree of nodal connectivity are given in Table 1.

The design domain in Fig.4a needs to have a void, thus some of the fields in the ground structure must be eliminated. In the software this is done by typing the mark of the right corner node of the field which must be eliminated. In the case of the compliant gripper the node mark 16 is selected and after this the new ground structure for the compliant gripper is obtained (Fig. 5).

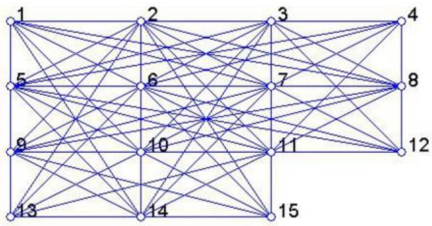


Fig. 5 Ground structure with a void

Next, input force F and supports need to be defined. This is done by typing the node mark in which the force and supports are to be put. The same stands for defining output displacement Δ. The user also needs to input the size and the orientation of the force and the displacement. For the specified cases, parameters for defining force, supports and output displacement are given in Table 1.

Table 1 Design specifications for compliant gripper and displacement inverter problems

Design parameters	Compliant gripper	Compliant displacement inverter
element modulus	E=2.1 GPa	E=2.1 GPa
design domain	60 mm × 30 mm	50 mm × 25 mm
grid size	4 × 4	3 × 2
force	node = 13; α = 180°; F = 30 N	node = 4; α = 180°; F = 2 N
supports	node = 1	nodes = 1, 3
displacement	node = 12; direction: y; Δ_{min} = 5 mm;	node = 6; direction: x; Δ_{min} = 2 mm;
element thickness	0.5 mm, 1 mm, 1.5 mm	0.5 mm, 1 mm, 1.5 mm
degree of nodal connectivity	3	2

When the problem is set, and the design specifications are defined, the software starts with the optimization procedure and the optimal solution of the given problem is searched.

4.2. Objective function

An objective function is needed to drive the optimizer toward a desired goal. The main goal in the synthesis of the compliant gripper and the compliant displacement inverter is to maximize the output displacement while meeting the given constrains. This is done by maximizing the ratio of output displacement Δ_{out} to input displacement Δ_{in} which is known as the geometric advantage.

All objective function terms are calculated from the results of the linear finite element analysis (FEA), implemented in the software, with only one beam element placed between each of the nodes in the topology being analyzed.

4.3. Constraints

Two constraint penalties are added to the objective function to monitor deflection. The first is a constraint that requires the output deflection in the desired direction be greater than minimum value Δ_{min}. The second constraint requires that the output deflection perpendicular to the desired direction, should be less than maximum value $\Delta_{min}^{\perp}$. Also, total element length (L_t) constraint is used; L_t is the sum of the lengths of all the elements in a given design, and primary intention is to reduce complexity, not necessarily weight. The final form of the objective function that is used in the software for the synthesis of the compliant gripper and compliant displacement inverter is:

$$maximize\left[\frac{\Delta_{out}}{\Delta_{in}}+w_1\cdot(\Delta_{out}-\Delta_{min})+w_2\cdot(\Delta_{max}^{\perp}-|\,\Delta_{out}^{\perp}\,|)-w_3\cdot|\,L_t-L_{target}\,|\right] \quad (1)$$

where w_1, w_2, and w_3 are relative weighting constants and L_{target} represents the desired total element length. In the formulation, the penalties are applied only when $\Delta_{out}<\Delta_{min}$ or $\left|\Delta_{out}^{\perp}\right|>\Delta_{max}^{\perp}$. The values for constrains and for weighting constants are given in Table 1 and Table 2.

4.4. Discrete nonlinear topology optimization

For a given model of the design space, the variables can be optimized via a Genetic Algorithm to yield a mechanism topology. Genetic Algorithms are a form of nonlinear optimization that seeks global optima, and are especially suited for discrete, nonlinear problems. Every design is evaluated with FEA, which is used to assign the above fitness function, Eq. (1).

In the software, to initiate the genetic search, the user must define the following parameters [14]: size of initial population which represents the number of randomly generated designs; number of Generations i.e. the number of iterations which will be used in the optimization process; crossover probability – the probability that crossover will be performed between a pair of parent designs (random number of element variables are swapped between two parent designs in the process of crossover); mutation probability – the probability that the design will mutate (elements in the design mutate to different thickness). The algorithm parameters used in the synthesis of the compliant gripper and the displacement inverter are:

initial population of 200 designs, total number of 500 generations, crossover probability of 80% and mutation probability of 9%.

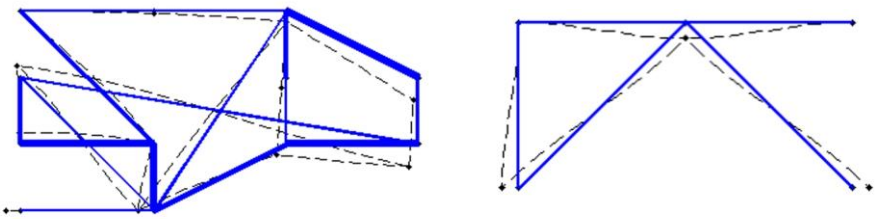
Table 2 Constraints used in the synthesis of the compliant gripper and the compliant displacement inverter

Constraints	Compliant gripper	Compliant displacement inverter
weighting constants	w_1=0.6; w_2=0.2; w_3=0.2	w_1=0.6; w_2=0.2; w_3=0.2
$\Delta^{\perp}_{max}$	5 mm	0.1mm
L_{target}	354 mm	214 mm

4.5. Results

After the optimization is finished, the software displays the obtained solution of the given task. The solution to the problem contains the compliant structure in which some of the elements are eliminated in the process of optimization. The remaining elements define the optimal topology of the compliant mechanism that can realize the given task.

The obtained results for the compliant gripper problem and compliant displacement inverter problem, by using the developed software, are shown in Fig. 6 [15].

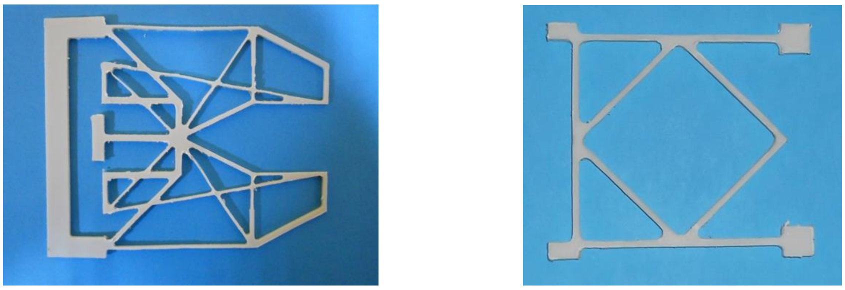


a) b)

Fig. 6 Optimal topology of the compliant gripper (a) and the displacement inverter (b), only the top-halves of the mechanisms are shown (deformed position is shown with dashed lines) [15]

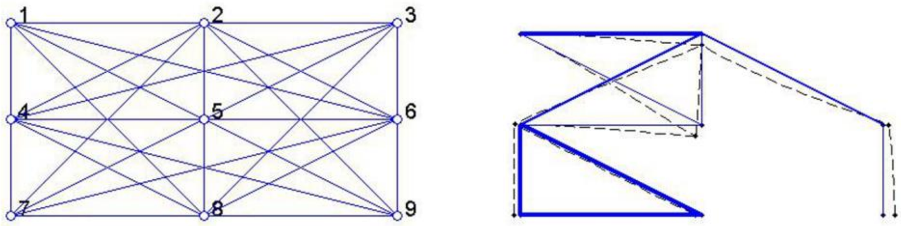
In both cases, the topology of the compliant mechanisms is optimized. When the force is applied at the input port the compliant gripper deforms and realizes the output deflection of: Δ_{out} =10.66 mm, and in the case of the displacement inverter the output deflection is Δ_{out} =17.93 mm. The geometrical advantage of the compliant gripper is Δ_{out}/Δ_{in}=1.42, and in the case of displacement inverter Δ_{out}/Δ_{in}=0.994. Finally, the results are verified via solid model finite element analysis [15]. Physical prototypes of the mechanisms in Fig. 6, made from plastic, are shown in Fig. 7.

Another optimization is run for the case of the displacement inverter but now with a higher grid resolution of the initial ground structure (Fig. 8a). Here the grid size 3x3 is used, the input node is 7 and the output node is 9 (all other design and algorithm parameters are the same as in the case of the displacement inverter in Fig.3b). The obtained solution is shown in Fig. 8b.



a) b)

Fig. 7 Physical prototypes, made of plastic, of the compliant gripper (a) and the compliant displacement inverter (b)



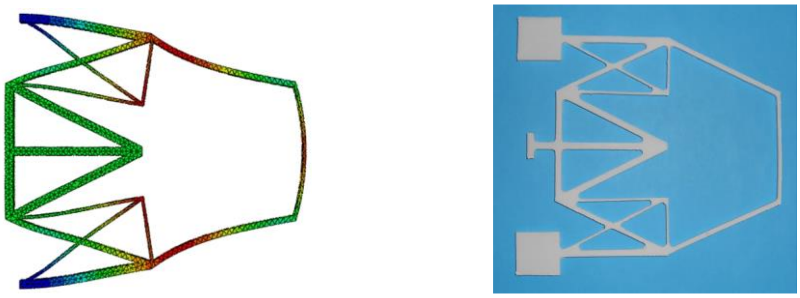
a) b)

Fig. 8 a) Initial ground structure; b) optimal topology of the displacement inverter, only the top-half of the mechanism is shown (deformed position is shown with dashed lines)

Due to the applied force at the input port (node 7) the compliant displacement inverter deforms and realizes the output deflection (node 9) of: Δ_{out}=2.0229 mm, while the displacement of the input port is Δ_{out}=1.0891 mm. The geometrical advantage of the obtained mechanism is Δ_{out}/Δ_{in}=1.8574. This means that a displacement inverter that has the geometrical advantage greater than 1 (thus acting as an amplifier) can be obtained if higher grid resolution is used (in our case the output displacement is nearly doubled). The results are verified via solid model finite element analysis (Fig. 9a). The analysis shows linear dependence between the input and the output displacement (the results are given in Table 3). The manufactured model of the compliant displacement inverter, made of plastic, is shown in Fig. 9b.

Table 3 Results of the finite element analysis for the compliant displacement inverter

Input displacement (mm)	Output displacement (mm)	Geometrical advantage
1	1.7427	1.7427
2	3.4854	1.7427
3	5.2281	1.7427



a) b)

Fig. 9 a) Finite element analysis of the compliant displacement inverter; b) mechanism prototype made from plastic (the whole mechanism is shown in both cases)

5. Synthesis of Compliant Mechanisms without Intersecting Elements

In the topology optimization of compliant mechanisms the choice of initial ground structure is very important as the ground structure represents the space of design variables in which the optimal solution (for a given problem) is searched for. In the literature, the reduced initial ground structure is commonly used [12] with the degree of nodal connectivity 1 (Fig. 10). Because the ground structure is reduced, nodes are placed at the intersection point between two elements i.e. in this ground structure intersections do not exist (Fig. 10). Although this kind of ground structure greatly reduces computation time and compliant mechanisms without intersecting elements are obtained, it cannot always efficiently represent the design domain; because of the reduction many of the good designs are lost at the beginning. Partially connected ground structure (Fig. 4) is also used in the literature [2], [7]. Although this kind of ground structure can more effectively represent the design domain (higher degree of nodal connectivity), the solutions with intersecting elements are obtained (as in Fig. 6a and Fig. 8b or see [2], [7]) where at the place of intersection the nodes are not defined. There are some differences between the results obtained by FEM analysis and by using the novel software in mechanisms in Fig. 6a and Fig. 8b, as at the places of intersection the nodes were not defined.

Defining the nodes at the intersecting points between elements would greatly increase the computational time because the ground structure becomes highly complex with many intersecting elements (Fig. 4a). A designer must keep in mind that when it comes to manufacturing of compliant mechanisms obtained with this kind of ground structure, elements that intersect themselves must be manufactured in separate planes. This can be sometimes very difficult to achieve. Other solution is to produce elements in the same plane with intersections (like in Fig. 7a and Fig. 9b), but then the stiffness of the system will increase and the functionality of the mechanism will decrease regarding the originally obtained mechanism. This deficiency has motivated us to improve the existing topology optimization technique so that the intersections between elements would be eliminated in the process of optimization. This represents a novel approach to the synthesis of compliant mechanisms.

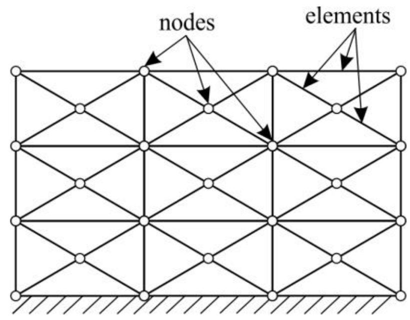


Fig. 10 Reduced initial ground structure

To eliminate intersections between elements in the topology optimization process, a computer-coded algorithm as a search filter is created. In every iteration during the optimization process, the algorithm searches for intersecting points between elements in the structure (Fig. 11). Then the total number of intersections (for every structure) is calculated. The goal is to eliminate all the intersections in the structure thus minimizing their total number represents the objective function term. Here the total number of intersections (n_{int}) is used as a constraint rather than an objective function term. The final form of the objective function that is used in the software for the synthesis of compliant mechanisms without intersecting elements is:

$$maximize\left[\frac{\Delta_{out}}{\Delta_{in}}+w_n\cdot(n\,various\ constraints)-w_{n+1}\cdot|L_t-L_{target}|-w_{n+2}\cdot n_{int}\right] \tag{2}$$

The synthesis of compliant mechanisms without intersecting elements will be shown on the example of the synthesis of the compliant gripper and the compliant displacement inverter.

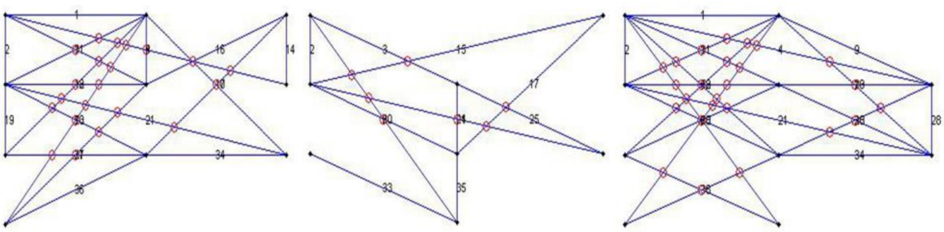


Fig. 11 Finding the intersections between elements in different steps of optimization

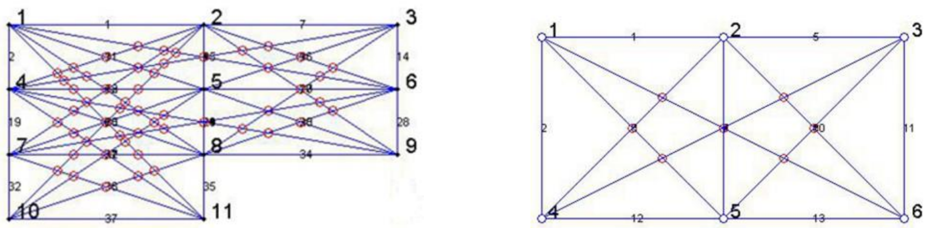
6. Synthesis of the Compliant Gripper and the Displacement Inverter Without Intersecting Elements

For the synthesis of the compliant gripper and the compliant displacement inverter without intersecting elements the same design domain is used as in Fig. 3. The only difference is that instead of the force, now the displacement is applied at the input port. Design specifications for both compliant mechanisms are given in Table 4.

Table 4 Design specifications for the synthesis of the compliant gripper and the compliant displacement inverter without intersecting elements

Design parameters	Compliant gripper	Compliant displacement inverter
element modulus	E=2.1 GPa	E=2.1 GPa
design domain	50 mm × 25 mm	50 mm × 25 mm
grid size	3 × 4	3 × 2
input displacement	node = 10; direction: x; Δ_{in} = 2 mm	node = 4; direction: x; Δ_{in} = 1 mm
desired output displacement	node = 9; direction: y; Δ_{min} = 1 mm	node = 6; direction: x; Δ_{min} = 0.5 mm
supports	nodes=1, 4, 7	nodes=1, 3
element thickness	0.5 mm, 1 mm, 1.5 mm	0.5 mm, 1 mm, 1.5 mm
degree of nodal connectivity	3	2

Initial ground structures with an initial number of intersections for the compliant gripper and the compliant displacement inverter problem are shown in Fig. 12 (intersections are shown with red circles).



a) b)

Fig. 12 Initial ground structure with an initial number of intersections: a) compliant gripper (number of intersections 81); b) displacement inverter (number of intersections 9)

The objective function used in the synthesis of the compliant gripper and the compliant displacement inverter is similar as in Eq. (1), where the constraint of the total number of intersections is now added (constrains are given in Table 4 and Table 5):

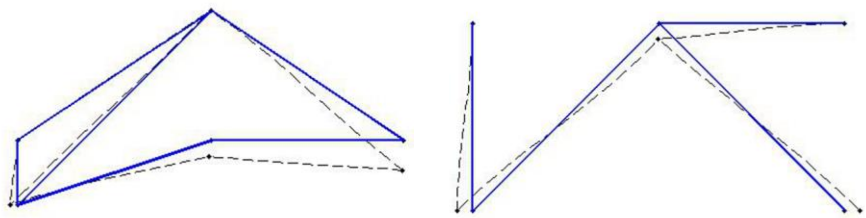
$$maximize\left[\frac{\Delta_{out}}{\Delta_{in}}+w_1\cdot(\Delta_{out}-\Delta_{min})+w_2\cdot(\Delta^{\perp}_{max}-|\Delta^{\perp}_{out}|)-w_3\cdot|L_t-L_{target}|-w_4\cdot n_{int}\right] \quad (3)$$

The algorithm parameters used in the synthesis of both compliant mechanisms are: initial population of 200 designs, total number of 500 generations, crossover probability of 80% and mutation probability of 9%.

Table 5 Constraints used in the synthesis of the compliant gripper and the displacement inverter without intersecting elements

Constraints	Compliant gripper	Compliant displacement inverter
weighting constants	w_1=0.3; w_2=0.3; w_3=0.1; w_4=1	w_1=0.3; w_2=0.3; w_3=0.1; w_4=1
$\Delta_{max}^{\perp}$	0.5 mm	0.5mm
L_{target}	167 mm	111 mm

After defining all the design and algorithm parameters, the optimization procedure is started and the optimal topology of compliant mechanisms is searched for. The obtained optimal topologies of the compliant gripper and the compliant displacement inverter are shown in Fig. 13.



a) b)

Fig. 13 Optimal topology of the compliant gripper (a) and the displacement inverter (b) without intersections, only the top-halves of the mechanisms are shown (deformed position is shown with dashed lines)

Unlike solutions in Fig. 6a and Fig. 8b here the compliant mechanisms without intersections are obtained. The results for both mechanisms are shown in Table 6.

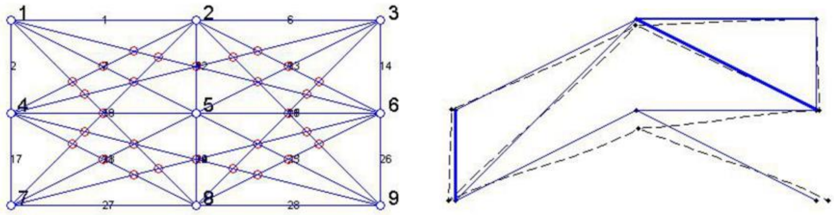
Table 6 Results for the obtained optimal topologies of the compliant gripper and the compliant displacement inverter without intersections

Results	Compliant gripper	Compliant displacement inverter with grid size 3×2	Compliant displacement inverter with grid size 3×3
output displacement	8.53 mm	0.996 mm	3.9023 mm
realized $\Delta_{max}^{\perp}$	0.40 mm	0 mm	0 mm
geometrical advantage: Δ_{out}/Δ_{in}	4.2693	0.996	1.9512
L_t	171 mm	120 mm	222 mm

The compliant gripper mechanism analysis shows that the mechanism expresses a better performance than the one with intersections (Fig. 6a). Geometrical advantage of the gripper mechanism without intersections is much greater than the one with intersections (Table 6). This is due to the fact that intersections between elements increase stiffness of the structure thus lowering the functionality of the mechanism. Because the geometrical advantage of the compliant gripper without intersections is greater than 1 (Δ_{out}/Δ_{in}=4.2693), the compliant gripper also acts as an amplifier of the output displacement in respect to the input displacement. It is important to note that the topology of the compliant gripper in Fig. 13a is mainly formed of elements that would not exist if a simplified initial ground structure was used (Fig. 10).

In the case of the compliant displacement inverter, both the compliant mechanisms in Fig. 6b and Fig.13b are without intersections. This is because the initial ground structure with a small grid size is used in both the cases and thus the number of possible solutions is small. Although the topology of the mechanisms is slightly different, their geometrical advantage is nearly the same (Table 6).

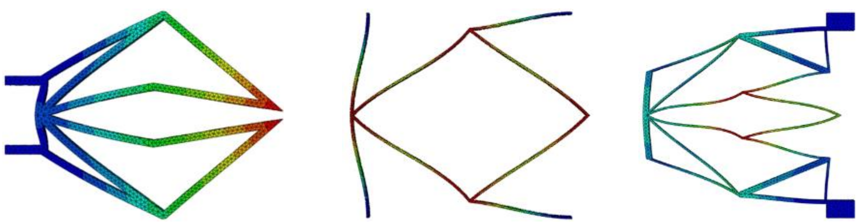
To confirm the elimination of the intersections in the case of the compliant displacement inverter, another optimization is run but now with higher grid resolution: 3x3 (Fig. 14a). All the other design and algorithm parameters are the same as for the displacement inverter in Fig.13b; here L_{target}=223 mm, the input and the output port are nodes 7 and 9, respectively. The optimal topology of the compliant displacement inverter is shown in Fig.14b. Again the compliant mechanism without intersections is obtained, unlike mechanism in Fig. 8b. The previously made conclusion is confirmed here, the compliant displacement inverter that has the geometrical advantage greater than 1 (thus acting as an amplifier) can be obtained with higher grid resolution (Table 6). Compared to the compliant mechanism in Fig. 8b, the geometrical advantage of the compliant displacement inverter without intersection is better (Table 6). Similar to the case of the compliant gripper, the optimal topology of the displacement inverter contains beam elements that would not exist if the simplified ground structure was used.



a) b)

Fig. 14 a) Initial ground structure with initial number of intersections (44); b) optimal topology of the compliant displacement inverter, only the top-half of the mechanism is shown (deformed position is shown with dashed lines)

All the results are verified via commercially available FEM analysis software (Fig. 15).



a) b) c)

Fig. 15 Finite element analysis of: a) compliant gripper; b) displacement inverter (grid size 3×2); c) displacement inverter (grid size 3×3)

7. CONCLUSIONS

This paper presents original software for an optimal synthesis of compliant mechanisms without intersecting elements. The software uses the topology optimization technique that is especially useful when the designer does not have a particular compliant mechanism already in mind. In the software the user only needs to input the problem specifications and the software then (through the topology optimization) automatically generates the optimal structural form (optimal topology) of a compliant mechanism which represents the solution for a given task. The methodology as well as the algorithm on which the software is built are also described. The existing topology optimization technique is improved so that compliant mechanisms without intersecting elements are obtained. This represents a novel approach to the synthesis of compliant mechanisms. The capability of the software with the newly introduced approach is shown on the example of the synthesis of two compliant mechanisms: a compliant gripper and a compliant displacement inverter, with and without intersecting elements for comparison. The optimal topologies of both mechanisms (with and without intersections) are obtained. The results show that compliant mechanisms without intersecting elements have better performances. It is also shown that the objective function in Eq. (2) and (3) will ensure that compliant mechanisms without intersecting elements will be obtained. All the results are verified via commercially available FEM analysis software and the physical prototypes of all the obtained mechanisms are manufactured (from plastic).

The developed software intends to provide an easy-to-use tool for the synthesis of compliant mechanisms that can be used by both experts and designers who are not necessarily familiar with the details of topology optimization techniques. We hope that this software will lead to the synthesis of compliant mechanisms that can provide new and better solutions to many engineering problems.

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SOFTVER ZA SINTEZU GIPKIH MEHANIZAMA BEZ PRESEČNIH ELEMENATA

Gipki mehanizam se definiše kao pokretna, materijalno koherentna struktura koja može da prenese sile i transformiše kretanje samo zahvaljujući elastičnoj deformaciji odgovarajučih segmenata strukture. Sinteza ove vrste mehanizama predstavlja izazovan zadatak, posebno zato što su njihovi elastični segmenti često izloženi velikim, nelinearnim deformacijama što zahteva znatno težu, nelinearnu analizu. Kada projektant nema unapred osmišljenu formu gipkog mehanizma za sintezu se uobičajeno koriste postupci optimizacije topologije. Preseci elemenata, koji postoje u gipkim mehanizmima dobijenim primenom postojećeg postupka optimizacije topologije, često povećavaju krutost strukture koja mora biti dovoljno elastična. U ovom radu je predstavljen novi softver za sintezu gipkih mehanizama koji unapređuje aktuelne postupke optimizacije topologije time što eliminiše presečne elemente odgovarajućih segmenata gipkog mehanizma. Metodologija koju softver koristi i njegove mogućnosti predstavljeni su na primeru sinteze gipkog hvatača i gipkog invertora pomeranja.

Ključne reči: *Gipki mehanizam, sinteza, optimizacija topologije, gipki hvatač, gipki invertor pomeranja*