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Structural topology optimization using multi-objective genetic algorithm with constructive solid geometry representation

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ABSTRACT

This paper presents a constructive solid geometry based representation scheme for structural topology optimization. The proposed scheme encodes the topology using position of few joints and width of segments connecting them. Union of overlapping rectangular primitives is calculated using constructive solid geometry technique to obtain the topology. A valid topology in the design domain is ensured by representing the topology as a connected simple graph of nodes. A graph repair operator is applied to ensure a physically meaningful connected structure. The algorithm is integrated with single and multi-objective genetic algorithm and its performance is compared with those of other methods like SIMP. The multi-objective analysis provides the trade-off front between compliance and material availability, unveiling common design principles among optimized solutions. The proposed method is generic and can be easily extended to any two or three-dimensional topology optimization problem by using different shape primitives.

1. Introduction

Structural optimization deals with the determination of the topology, shape and size of the structures and mechanism, starting with a domain of material to which the external loads and supports are applied [1]. Structural topology optimization can be considered as determination of material connectivity among different ports such as input, output and support ports (boundary conditions). These special ports and other material intersection ports can be termed as nodes and the topology defines the connection between such nodes. The objective function is often the compliance, that is, the flexibility of the structure under the given loads, subject to a volume constraint. The distribution of material is measured in terms of the overall stiffness of the structure such that the higher the stiffness, the more optimized the distribution of the allotted material in the domain.

Few of the most popular methodologies in this field of research include the homogenisation method [2], Solid isotropic material with penalisation (SIMP) [3,4], level set methods [5,6], evolutionary structural optimization [7], etc. Approaches such as SIMP, assign the pseudo-densities of the ground elements as the design variables. Ground elements with low-density values represent voids in the structure whereas the elements with high densities result in solids in the structure. Gradient-based methods such as the method of moving asymptotes (MMA) and sequential linear programming (SLP) are mostly preferred for optimization. Known problems with this technique are point flexure, mesh dependency and gray areas, which are often dealt with using different filtering techniques [8] or combining it with other methods like simulated annealing [9,10] to fix elements with intermediate densities.

There have been some attempts to use evolutionary algorithms (EAs) for topology optimization where traditionally, the method is based on ISE topologies i.e. Isotropic Solid or Empty ground elements of fixed boundaries [11]. In these methods, any ground element is either filled completely by a given isotropic material or contains no material. Each ground element may consist of one or several finite elements. Genetic algorithms (GAs) were used by Jakiela et al. [12] for the optimal topology search of continuum structures. The design space was discretized into small elements with all of the finite elements forming a binary-coded bit-string chromosome, 0 and 1 for absence and presence of an element in the structure, respectively. It was found that EAs search performances are incomparable to the gradient-based methods. This is because most, if not all of topology optimization problems have a great many design variables. Since the EAs somewhat base their searching strategies on direct search, they are not as powerful when solving such a large scale design problem [13,14]. Hence a need to improve the non-gradient based EA is understood. With an improved searching performance, using EAs for topology optimization would be advantageous because of the global search and the possibility of easily dealing with unconventional topological design problems, which may be difficult or even impossible to be solved by using the gradient-based optimisers. To overcome these problem, an approach of gradually refining the design domain has been proposed in [15]. Results for short cantilever and bridge problems are demonstrated to be better than brute-force GA application. [16] provides a method based on the concept of design space separation through the simultaneous application of multiple genetic algorithms and the use of structural response information to guide the GA. In [17], the authors propose an approximate density distribution method and use it in a modified simulated annealing method [18] with improved performance for topology optimization problems. Madeira et al. [19] propose a multi-objective GA with volume preserving chromosomes. Compliance for different boundary conditions are used as objectives to solve two and three dimensional problems. In [20], Bureerat et al. use a combination of ground element filtering technique and evolutionary algorithms to do a comparitive study of different multi-objective evolutionary algorithms on topology optimization problems.

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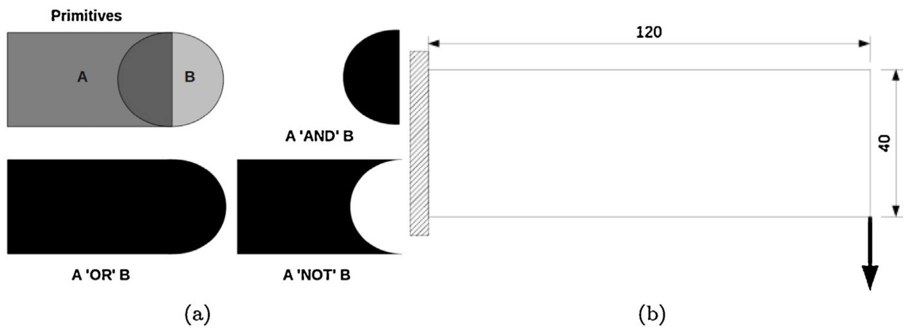

Fig. 1. (a) CG Boolean operations on circular and rectangular 2-D primitives. (b) Problem domain for cantilever with end loading.

The grid representation not only causes large number of design variables but also limits formation of thin sections in the topology. New representation schemes like Voronoi-based representation [21] and morphological geometric representation scheme have also been proposed. Tai et al. [22] utilize the latter with spline based arrangements of skeleton and flesh surrounding the bones to represent structural geometry. The work is further extended by using graph representation GA in [23] which shows improved results compared to Voronoi-bar representation. Garcia et al. [24] use Tai's representation scheme of B-splines for multi-objective optimization to simultaneously minimize expected compliance, variation of compliance and volume. This gives different choices to the designer in case of uncertainty of input. Other recent works in non-gradient methods include simulated biological growth (SBG) [25], bidirectional evolutionary structural optimization (BESO) [26], cellular automata [27] and ant colony optimization [28].

In the current work, a graph based variable encoding scheme using Constructive Solid Geometry (CSG) is proposed. CSG is a technique widely used in solid modelling. It uses Boolean operators (shown in Fig. 1(a)) to combine simple objects called solids or primitives, constructed according to geometric rules, and form complex two or three dimensional geometries. Simple shapes like rectangle, circle, ellipse or a generic polygon can be used as a CSG primitives in 2-D. The Boolean operations can be summarized as union, intersection and difference as shown in Fig. 1(a). The operations are shown on a rectangular and circular primitive in it. The idea of utilizing CSG primitives to reduce the design variables provided the motivation for the proposed technique. We use CSG union of many overlapping rectangular shaped primitives to form complex shape segments. The material where primitives do not appear is left out as holes.

Section 2 describes the details of the algorithm with a sample example of cantilever beam and Section 3 proposes a graph repair operator to ensure validity of topology. Single and multi-objective problem formulation is done in Section 4 and compliance minimization test problems are solved next in Section 5. Five single objective test cases are solved to give minimum compliance optimized structure, while its multi-objective counterpart in Section 6 throws light on trade-off existing between material availability and compliance. Finally the concluding remarks in Section 7 summarize the work and discuss scope of future studies.

2. Proposed methodology

The synthesis of compliant mechanisms has traditionally been viewed as a domain with presence or absence of holes. On the contrary, we propose to use a building-block model where different segments (primitives) overlap to give shape and volume to the final topology. Fig. 2 diagrammatically presents the multi-objective optimization flowchart along with variable decoding scheme. The key idea is to view a generic topology to be comprising of joints and rectangular segments connecting the joints. The optimization aims to find the connectivity and optimum position of joints along with the dimensions of segments. For a topology optimization problem, domain, boundary conditions (supports) and loads are specified initially. Without loss of generality, the scheme is explained by an example of cantilever domain of dimensions 120 mm × 40 mm fixed at one end and with a point load applied at the lower right corner, as shown in Fig. 1(b). The decoding scheme can be summarized in following steps

- Define joint positions.
- Define connectivity between joints.
- Ensure topology validity.

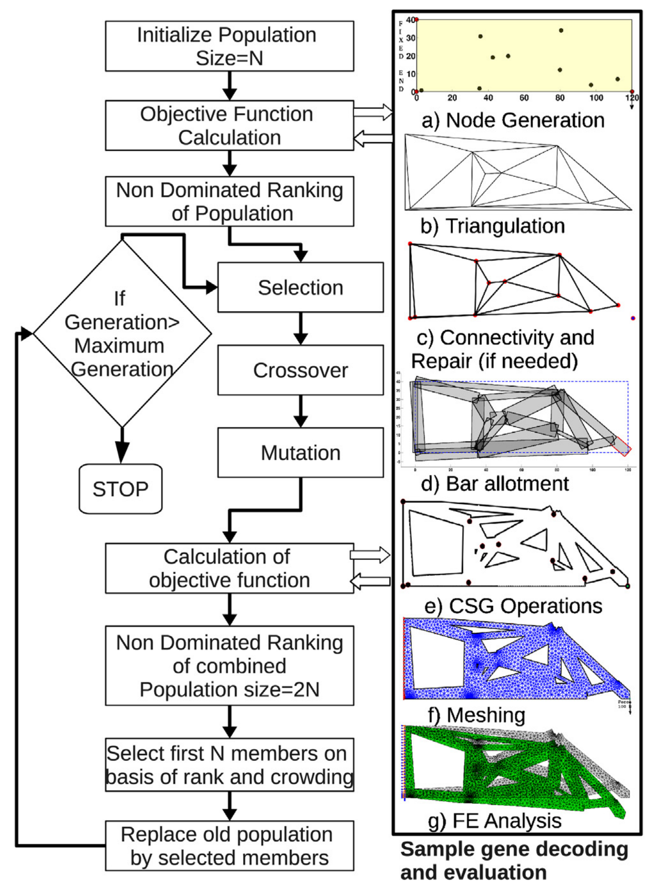

Fig. 2. Flowchart of proposed GA.

- Define the shape of segments connecting joints.
- Obtain topology by union of overlapping primitives.
- Meshing and finite element analysis.

2.1. Defining nodes

The representation scheme completely defines the structural topology by $2n + \binom{n+k}{2}$ real variables in computational space, which are decoded to form a topology in geometrical space. Here n is number of variable nodes chosen by user and k is number of fixed nodes. After considering the boundary condition and loads, user defines k fixed nodes, representing spatial locations where material must necessarily be present. The representation scheme ensures that segments connecting these fixed nodes to the topology are always present. Hence they are generally chosen at point