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Combining structural performance and designer preferences in evolutionary design space exploration

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ABSTRACT

This paper addresses the need to consider both quantitative performance goals and qualitative requirements in conceptual design. A new computational approach for design space exploration is proposed that extends existing interactive evolutionary algorithms for increased inclusion of designer preferences, overcoming the weaknesses of traditional optimization that have limited its use in practice. This approach allows designers to set the evolutionary parameters of mutation rate and generation size, in addition to parent selection, in order to steer design space exploration. This paper demonstrates the potential of this approach through a numerical parametric study, a software implementation, and series of case studies.

1. Introduction

In the conceptual design of buildings and bridges, designers must consider a wide range of goals related to performance. These include quantitative, measurable goals such as structural efficiency, cost, and embodied energy, as well as qualitative goals that cannot be expressed numerically, such as aesthetics, constructability, and contextual appropriateness. The designer's early-stage responsibilities include balancing these requirements to attain a satisfactory initial design concept.

Since the advent of computational tools, digital methods have emerged to help designers assess both quantitative and qualitative performance. For example, structural analysis software provides feedback on structural performance, and computer-aided drawing and modeling software can produce images and renderings that convey aesthetic performance. However, few computational tools exist that allow the designer to consider these two types of performance in one environment. Furthermore, while most widely used tools provide feedback to the designer, very few provide guidance, or suggested changes for design improvement. This leads to designers using software in a time-consumingtrial-and-error mode that limits the number of design alternatives that can be considered, potentially reducing the quality of the chosen solution.

A potential remedy for design guidance is optimization, an approach that computes the best performing solution according to mathematically formulated objectives and subject to mathematically formulated constraints. There are a multitude of available optimization algorithms, but nearly all require the objective function to be quantitative. This means that while optimization can address some conceptual design needs, it is not an appropriate approach for meeting unquantifiable yet important goals.

The mismatch between optimization's capabilities and the needs of the practical design process is one likely reason for the limited adoption of optimization in the building industry [1]. A second, related reason deals with the concept of the optimum itself: since many qualitative goals are also subjective, it is impossible to say that one design solution is unequivocally the best in most design problems. Moreover, the combination of two or more competing goals leads to a subjective problem in deciding the relative tradeoff, even when both goals can be objectively evaluated on their own. Furthermore, goals in conceptual design are sometimes fuzzy or unknown, and designers adjust what they are looking for during their design explorations. To support adaptive goal adjustment, an ideal computational approach should expose designers to a diverse range of alternatives that may inspire new goals or spark new ideas. Because optimization produces a single solution to a design problem, it is unable to serve this role in its traditional form.

As an illustration of these issues, Fig. 1 shows a simple geometry optimization problem for a planar truss and the resulting design space for a weight minimization objective. This problem has two local optima, shown in the figure. However, it is also noteworthy that the design space is relatively flat; this means that there are many designs that vary significantly in their geometry while performing similarly to the optimal designs. Fig. 1 also shows three groups of designs that perform

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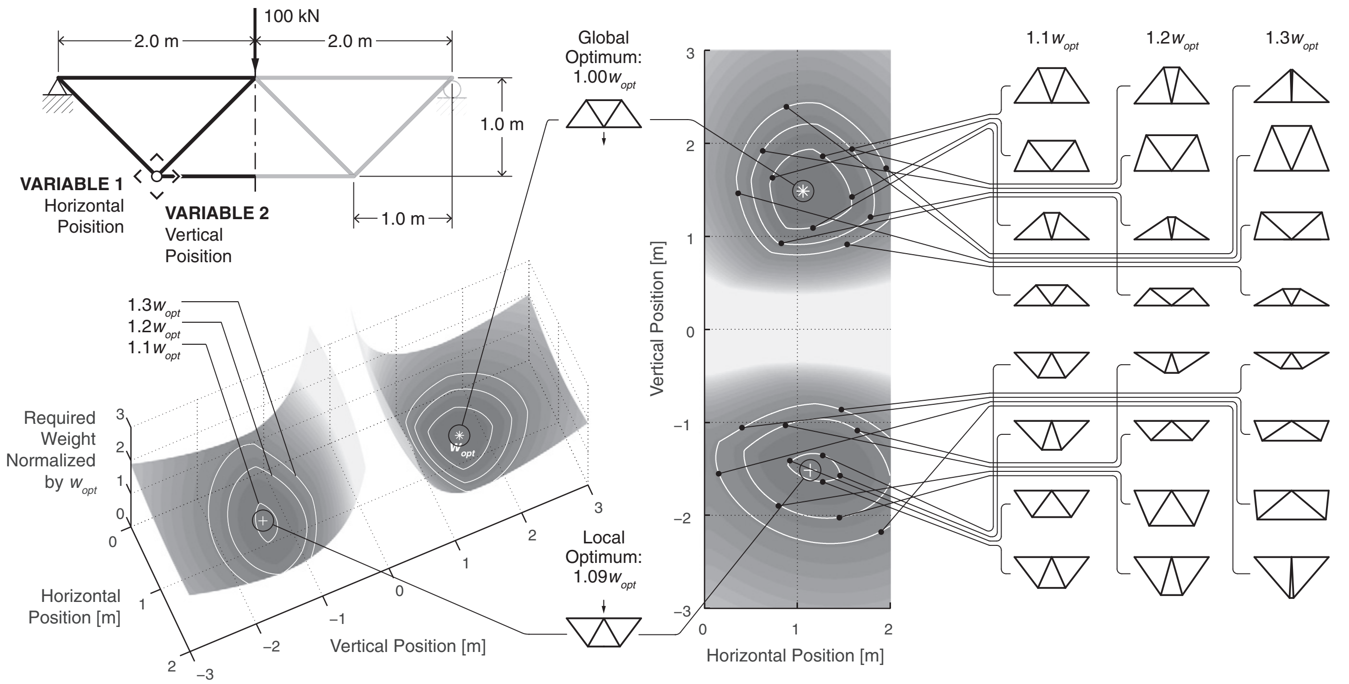

Fig. 1. A weight minimization problem for a seven-bar planar truss with two design variablesand the resulting design space. The global and local optimal solutions are shown, along with isoperformance contours for 1.1, 1.2, and 1.3 times w_{opt}, the optimal design's weight. For each contour, eight designs are highlighted, illustrating the aesthetic diversity of designs that perform almost as well as the best solution.

within 10%, 20%, and 30% of the global optimum respectively. These designs exhibit significant aesthetic diversity despite their similar structural performance.

A second example is shown in Fig. 2, which depicts two design alternatives for the lateral and gravity load-resisting system of an airport terminal. The first design is a standard rigid frame, while the second is a shaped frame of similar volume that creates a richer architectural experience by opening the interior space up toward the windows, with more structural depth in the back of the space. Due to the static indeterminacy of a fixedbase rigid frame, many high-performing options for the shaped inner profile are possible, and again, there are opportunities to meet unformulated, qualitative goals by compromising slightly on quantitative performance, and to provide a much broader range of design possibilities.

The research presented in this paper aims to take advantage of these opportunities by providing a way for designers to explore structural design solutions in a directed, performance-conscious manner. In contrast with standard optimization, the approach used here addresses qualitative design goals and constraints by incorporating input from human designers, in addition to considering formulated quantitative objectives. This type of optimization algorithm is classified as interactive (sometimes called human-guided or human-computer) optimization and is able to overcome the previously stated drawbacks of more conventional approaches.

1.1. Interactive optimization

Interactive optimization comprises a broad class of algorithms and approaches united by the inclusion of human input in the optimization process. An overview of the range of these approaches is given in [2]. Like standard optimization methods, interactive optimization methods can be divided into two groups: those that use gradient information and those that use heuristics. Gradient-based methods have the advantage of better performance and guaranteed convergence rates but are usually limited to design spaces that have mathematical properties not usually found in practical problems, such as continuity and differentiability. Heuristic methods are slower and cannot guarantee convergence but often perform reasonably well over a broad range of problem types encountered in practice.

These two types of approaches can be extended to include interactivity in different ways. Interactive gradient-based methods generally incorporate human input in the form of the initial design considered since in nonconvex design spaces the local optimum found depends on the starting position. This approach allows the designer to choose a

Fig. 2. Two options for the design of the lateral and gravity structural system for an airport terminal: (a) a standard rigid frameand (b) a shaped rigid frame, which uses a similar amount of material and creates a more architecturally expressive interior space.