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Multi-objective, multi-domain genetic optimization of a hydraulic rescue spreader

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ABSTRACT

In this paper, general strategies are presented by which a multi-domain, multi-objective, mechanism-based optimization problem may be efficiently formulated and solved by means of a genetic algorithm. These strategies include integration of traditional precision position techniques with genetic optimization, efficient selection of design variables and search bounds, and a nested optimization structure. A case study illustrating these methods is presented in which a hydraulic rescue spreader is simultaneously optimized for four objectives relating to structural efficiency and kinematic behavior. The solution obtained is shown to be equal or superior to a comparable commercially available device with respect to all four objectives.

1. Introduction

Traditionally, the process of designing a mechanism for a given task has consisted of a purely kinematic synthesis, with the design of the mechanical implementation being relegated to a subsequent separate phase. Classic closed-form techniques described by Sandor [1], Erdman [2], Kaufmann [3], and Loerch et al. [4] deal with exact synthesis of mechanisms to achieve desired task specifications at a number of precision positions. The main limitation of these methods is that only a small number of positions can be prescribed, with the motion being uncontrolled at other points.

Adaptations of the precision point approach that allow higher numbers of points to be specified in exchange for relaxing the precision of the synthesis also exist. Kramer and Sandor presented the Selective Precision Synthesis technique [5], where the synthesized path need only pass within a specified distance of each prescribed point instead of hitting it exactly. A variation is described by Mirth [6], who uses a combination of solving three exact point prescriptions using Burmester theory with a number of additional quasi-precision points that serve to narrow down an optimized final selection from the set of Burmester solutions. A number of authors have described least-squares type approaches that perform an approximate fit to a prescribed function [7,8], which is the same sort of strategy but with the prescription information distributed over the entire function rather than concentrated at a few precision or quasi-precision positions.

In more recent years, the application of genetic algorithms (GAs) to mechanism synthesis and optimization has given designers a powerful new capability. For example, Kunjur and Krishnamurty [9], Cabrera et al. [10], Laribi et al. [11], and Kanarachos et al. [12] all used single-objective GAs to synthesize a linkage to approximate a prescribed precision point motion. Fang [13] and Zhou and Cheung [14] performed similar tasks, but with the addition of novel features such as simultaneous type synthesis and an adjustable linkage respectively.

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While these techniques have successfully addressed the solution of the path, motion, and function generation problems found in kinematic design, they are restricted to a single optimization objective. GAs represent not just a more effective way to solve the traditional single-objective formulations of kinematic optimization, but also provide a natural framework for implementing multi-objective approaches that can achieve greater flexibility and realism. A number of applications of multi-objective genetic algorithms (MOGAs) exist in the literature. Cabrera et al. [15] simultaneously optimized the kinematics and grasping ability of a robotic manipulator. Nariman-Zadeh et al. [16] synthesized a four-bar linkage using a two-objective approach, in which the minimization of deviation of transmission angles from 90° was added to the common path tracking objective. Khorshidi et al. [17] similarly optimized for path tracking, transmission angle deviation, and also worst-case mechanical advantage, but introduced an integrated local search refinement that compensates for the tendency of GAs to miss the exact locations of optima with their limited number of objective function calls. El-Kribi et al. [18] minimized required input torque and input velocity fluctuation, and took the innovative approach of using selection from a list of actual motors as a discrete design variable.

These cases of multi-objective optimization of mechanisms differ from the present work in that they are fundamentally single-domain; that is, they restrict themselves to optimization of kinematic and dynamic properties of mechanisms, the realm of traditional kinematics. It must be recognized that the transmission of force and motion by a mechanism is not done in a vacuum and that there will be complex devices manifesting a variety of physics coupled to the mechanism at the inputs and outputs. In many cases a truly optimal design can only be reached by considering all parts of the system as an integrated whole, by means of a unified multi-domain optimization. Taking a historical view of mechanism design strategies, successive improvements were obtained over the original precision point techniques by the use of numerical optimization, single-objective GAs, and finally multi-objective GAs. It is the belief of the authors that extension to multi-domain considerations represents the natural next step in this evolution.

The utility of the multi-objective, multi-domain approach is illustrated by its application to the problem of optimizing a hydraulic rescue spreader. Hydraulic rescue spreaders, also known by the brand name “jaws of life”, are hydraulically actuated mechanisms used in emergency situations to remove victims trapped inside wreckage, often as a result of automobile accidents. They are composed of a linkage that converts the motion of a hydraulic cylinder to the spreading action of a pair of jaws. A typical rescue spreader and motion schematic is shown in Fig. 1.

Generally the jaws must exert a large force to deform various metal structures, resulting in large loads throughout the linkage. As the rescue spreader is an emergency tool that must be used with relative speed and ease by a single operator, care must be taken in the design process to minimize the mass, forming one of the optimization objectives. The other objectives involve kinematic characteristics of the mechanism: the jaw tips must achieve a large enough spreading distance to be effective without requiring too much rotation of the jaws, which can make it difficult for the tips to grip material effectively. This requirement tends to favor long jaws that can achieve large spreads with small rotations; however, this trend is structurally less sound and the structural analysis for the mass minimization will drive the design in the opposite direction, as will a third objective, namely minimization of the physical size of the mechanism for ease of use purposes. Finally, variation in the spreading force as the mechanism moves is minimized, as current models often suffer from low spreading force in the closed position compared to the open position. In short, the following four objectives are defined for the rescue spreader optimization problem:

1. Minimize mass
2. Minimize mechanism length
3. Minimize jaw rotation
4. Minimize variation in spreading force.

2. Kinematic analysis

2.1. Preliminary application of analytical synthesis

The dimension of the design space is determined by the number of design variables needed to describe the mechanism. Even a simple pin-jointed four-bar requires nine design variables if no other constraining considerations are present, and more complex linkages will have correspondingly larger design spaces, without even considering additional variables needed to capture non-kinematic aspects of the problem. As the difficulty of an optimization is strongly dependent on the dimension of the design space, it is very beneficial to be able to reduce the dimension before the optimization begins.

If the problem at hand includes a prescription of some aspect of the motion in addition to an optimization requirement, such a reduction can be achieved by preliminary application of an exact path, motion, or function generation synthesis technique. It is well-known that the classic precision position synthesis techniques will result in multiple infinities of solutions if the number of prescribed positions is less than the maximum allowable for that technique [19]. For example, in the case of function generation synthesis the prescription of seven positions will result in a finite number of solutions, but if fewer than seven positions are used, the synthesis results in a solution space of dimension equal to the reduction in the number of positions [20]. If this solution space is then taken as the design space of the optimization, it will likely be significantly more tractable than in the unconstrained case.

In the case of the rescue spreader, a two-position motion generation problem is used in this manner. Fig. 2 shows the spreader mechanism, which is fully described by a four-bar linkage if the half-symmetry of the full six-bar is taken into account. This figure introduces the notation used throughout this paper, in which a vector in the plane is denoted by the vector notation $\overrightarrow{R_i}$, with the length of that vector being given by the lower-case of the same letter, e.g. r_i.