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Research paper

Topology optimization of industrial robots: Application to a five-bar mechanism

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ABSTRACT

Recent works introduced topology optimization in the design of robots, but the proposed methodologies led to a local optimization of the performance. Moreover, most of performance indices used are not in strong relation with easy-to-understand technological requirements.

We propose a methodology that is able to perform a topology optimization for robots, valid globally in the workspace or for a set of given trajectories, and which is based on the use of technology-oriented performance criteria. In order to enforce the chosen performance indices to be valid globally, optimal robot configurations or trajectories for which extreme performance will be attained are computed, and iteratively updated.

In order to decrease the computational time associated with these performance indices, we exploit the structure of the elastic models in order to reduce their computational complexity.

Finally, we use an optimization algorithm called the Linearization Method which gives results in a computational time equivalent to standard topology optimization algorithms, but its implementation is less complex and makes it quite easy to perform modification or improvement.

The methodology is applied for the design of a five-bar mechanism. We show that our approach leaded to a robust optimization of the robot performance over the whole workspace.

1. Introduction

Robots are expected to perform a large variety of tasks. However, it is not wise to believe that a single robot will be able to achieve all conceivable tasks. Inherent robot limitations arise from its own physical performance (accuracy, deformation, vibrations, etc.), which are a combination of the performance of the mechanical architecture and of the controller.

Good performance of the mechanical architecture can be obtained via optimal design [1]. The usual design methodology proposed by French [2] is illustrated in Fig. 1. The first step is to analyze the need in order to formulate the design problem. The second phase focuses on the preliminary design and aims to synthesize design concepts (for instance, new types of robot architectures [3,4]) and to select the best design alternatives with respect to given criteria (e.g. complexity [5], singu-

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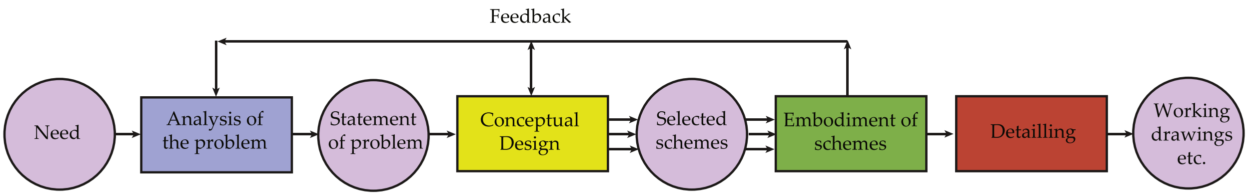

Fig. 1. French design process [2].

larity [6]). The third phase, denoted as the advanced design phase or embodiment of schemes, deals with the computation of the dimensions and shapes of the product element in order to fulfill performance criteria in terms of:

- geometric performance: e.g. workspace size and shape under joint limitations, link collisions [7,8], accuracy under input errors [9], under clearance [10,11] or link manufacturing errors [12],
- kinematics / kinetostatics: e.g. velocity transmission ratio [13–15], effort transmission [16–21],
- dynamics: e.g. moving mass reduction [22], maximal input torques [23], static [24] or dynamic balancing [25,26] conditions, decoupled structure of the dynamics equations [27,28],
- elasticity: static or dynamic deformations, natural frequencies and vibrations [29–31].

The fourth phase is the detailed design stage and consists in obtaining the working drawings of the product elements, in synthesizing their dimensional and geometric tolerances [32], and in manufacturing the prototypes.

The design optimization problem treated in the advanced design phase is usually formulated as a multicriteria optimization problem and it is most of the time solved in cascade in order to reduce its complexity [22]. In a first step, the multicriteria optimization problem takes only into account geometric, kinematic and kinetostatic constraints and objectives and allows for fixing the primary geometric parameters of the robot (lengths of links, angles between the joint axes etc.) [33]. In a second step, the secondary geometric parameters are found (size of the link cross-sections, link mass distribution, or more generally link shapes) taken into account dynamic, elastostatic and elastodynamic aspects [23].

The link shape optimization of robots is probably the most time-consuming step of the optimal design process. This is due to the complexity of the model involved, especially the elastic models, which must be computed thousands of times (and even more) in order to calculate the robot elastic performance in many robot configurations for a given set of design variables [22]. This is necessary in order to ensure that the performance can be guaranteed in a wide range of robot configurations [15]. As a result, in order to decrease the time of computation, a common approach is to reduce the number of design variables. It can be easily reduced by doing a parametric optimization [22,31], i.e. by modeling links using beam theory [34] and by considering that the geometry of the beam cross-sections is fixed (for instance, circle, square, rectangle, I-shape) but parameterized by a limited number of variables (radius for circles, edge lengths for squares, rectangles, I-shapes).

This approach is known not to be the more accurate for finding the optimal design of links, contrary to topology optimization [35]. Topology optimization was for instance used for the design of compliant mechanisms [36–38]. This latter technique aims at optimizing the material distribution in a link in order to satisfy performance criteria: a classical problem met in the literature is to minimize the link mass under compliance constraints [39]. The link shape is meshed, and deformation and vibration models are computed using Finite Element Methods (FEM) [40]. The presence of one element of material is parameterized by a design variable varying from 0 to 1, 1 means that there is material while 0 represents a void. As a result, in order to have a refined prediction of the link behavior and a refined visualization of the link shape, this method usually leads to a vector of design variables in the optimization process containing dozens of thousands of components. Topology optimization is thus most of the time computationally expensive due to both the complexity of the models involved and the high number of design variables. Therefore, it is few used in robot design.

However, recent works introduced this technique in the design of robots. First attempts optimized the robot topology for a single loading case. For instance, Albers et al. [41] optimized the torso of a humanoid robot with an objective of minimal mass under compliance constraints while Lohmeier et al. [42,43] optimized the pelvis of a walking robot. Kwon et al. [44] employed topology optimization method to develop stiff and light frames of the lower body for stable walking of their humanoid robot. Yunfei et al.[45] and Huang and Zhang [46] both optimized the shape of the upper-arm for a 6-degrees-of-freedom (dof) industrial robot. Oliveri et al. [47] improves the shape of a chassis for a mobile robot.

Optimizing the robot link shapes for a single loading case does not take into account the intrinsic nature of a robot whose performance varies with the configuration, the loading and with the time. Therefore other works proposed alternative approaches. For instance, Albers et al. [48] and Albers and Ottnad [49] considered a given set of reference control signals for the motion of the robot arm and look at some robot performance, such as overshoot, controller settling time, number of oscillations, final deviation or also actuator energy consumption. Kim et al. [50] optimized the link shapes of 3-dof robots under varying configurations while addressing the problem of the reduction of the computational time by dividing the optimization problem into subproblems with lower computational complexity. They minimized the strain energy while constraining the robot mass. Hong et al. [51] optimized the shape of the pelvis of a humanoid robot by using equivalent static loads with the objective to minimize the strain energy.