Mechanism and Machine Theory 116 (2017) 69–88

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Optimal design of a parallel structure used as a haptic Interface☆

Catalin Boanta[a,*], Akos Csiszar[b]

[a] Department of Mechatronics and Machine Dynamics, Technical University of Cluj-Napoca, Cluj-Napoca, Romania
[b] Graduate School of Excellence advanced Manufacturing Engineering (GSaME), University of Stuttgart, Stuttgart, Germany

A R T I C L E I N F O

Article history:
Received 4 October 2016
Revised 27 March 2017
Accepted 9 May 2017

Keywords:
Optimization
Genetic algorithm
Parallel robot
Haptic
Workspace
Human arm

A B S T R A C T

The design of mechanical structures is a task which requires a large amount of experience. Experience can only be gained with time and this represents a disadvantage for junior engineers. However, using optimization methods, inexperienced engineers can achieve optimal results. One application for optimization methods in engineering is the design of mechanisms. The design problem can be formulated as an optimization problem, and so the optimal solution can be found using optimization, regardless of the experience of the design engineer. The aim of this paper is to present how the design of a parallel structure can be formulated as an optimization problem, how the factors influencing the design are incorporated in the problem formulation as goals or constraints. The developed theoretical aspects are then applied for the optimization of the parallel structure. Since the application of the optimized structure is a haptic device, the goal is to minimize the difference between the workspace of the robot and the defined most used part of the workspace of the human hand. Genetic Algorithms have been chosen to carry out the optimization. Results show that the method has dimensioned the design variables in a manner that corresponds to the formulated goal.

1. Introduction

The optimization represents the act of finding the best result of a problem subject to a given environment or circumstances. Generally, this aspect translates into the minimization of a function in a given context. The first advances in theoretical optimization (i.e. finding an extreme point of a function) was proposed by Descartes when he developed a method to solve the tangent line problem [1]. Later on, Newton and Leibniz have developed methods to reach an optimum point using calculus-based procedures.

Despite the fact that theoretical optimization methods have been thoroughly studied since Descartes has proposed his method, with an increased interest in the 20th century when the advances of the industry have amplified, the growth in computational power in the late nineties has emerged to a major interest in the optimization algorithms. Nowadays, fields as mechanics, engineering, economics, or geophysics, are constantly dealing to using optimization algorithms to find solutions several problems.

☆ All authors contributed equally to this paper.

* Corresponding author.
E-mail addresses: Catalin.Boanta@rezi.utcluj.ro (C. Boanta), Akos.Csiszar@gsame.uni-stuttgart.de (A. Csiszar).

http://dx.doi.org/10.1016/j.mechmachtheory.2017.05.013
0094-114X/

With regard to the mechanical design, the use of optimization methods overcomes the large amount of experience required to design the most advantageous mechanism for a given task. Consequently, using optimization algorithms, even inexperienced engineers can achieve adequate results. The optimization algorithms are capable to compute the best or almost best geometric, kinematic or dynamic parameters of a mechanism taking into consideration the requirements given by the application scenario. The application of the mechanism optimized in this paper is a haptic interface.

The term haptic interface refers to a device that allows the interaction of a human with a remote object in a physical or simulated environment. The human operates directly the haptic interface and his input is transferred to the object. The haptic interface responds to the input of the human input with a force or motion in order to induce the feeling of direct interaction with the object. The ReHapy concept, firstly published in [2] proposes the use of reconfigurable parallel structures in order to induce haptic sensations at the upper limb level. Therefore, it is desired that some properties of the mechanical architecture of the haptic interface to be as similar as possible with the functional characteristics of the upper limb of a human.

The aim of this paper is to present how the design of a parallel structure can be formulated as an optimization problem, how the different factors influencing the design can be incorporated in the problem formulation as goals or constraints. The novelty of this paper is the development of an optimization method of a robot that assures that an irregular-shaped 3D volume (called input or prescribed workspace) is included in the workspace of the optimized robot. The general case is exemplified with the optimization of a parallel robot used as a haptic interface in order to include in its workspace the most used part of the workspace of the human arm. An adequate design of the parallel structure leads to a workspace that is as similar as possible to the workspace of the human arm.

The entire system that defines this optimization problem is composed by:

1. The workspace of the human arm that is the input into the optimization problem.
2. The workspace of a parallel structure, that has to be as similar as possible with the input.
3. The design parameters that represent the geometrical characteristics of the elements of the parallel robot.
4. The optimization algorithm - the chosen algorithm has been the Genetic Algorithm.

The optimization problem presented in this paper has possible application in the design of both serial and parallel robots where several conditions have to be respected by their workspace.

There are several types of workspaces illustrated in the scientific literature. These types include constant orientation workspace [3], dexterous or reachable workspace [4]. The work addressed in this paper focuses on the constant orientation workspace of the parallel robot. Since the application of the parallel robot is a haptic interface, its workspace is desired to be as similar as possible to the workspace of the human arm.

Regarding optimization purposes, there are many scientific articles that propose the optimization of the architecture of serial or parallel robots by imposing several constraints to the workspace. In most cases, the main constraints that are imposed to the workspace is maximization or minimization of one or more properties like dexterity, volume or stiffness. By contrast, this paper focuses on a condition that takes into consideration the similarity between two workspaces, not maximizing or minimizing a property. In this paper, the similarity between two workspaces has been considered in the following case. The workspace of the robot that is optimized shall include a irregular 3D space (the prescribed workspace) that is the input into the optimization. Moreover, the part of the workspace of the robot that lies outside of the boundaries of the input workspace has to be minimal. Therefore, in ideal case, two similar workspaces are identical.

On the subject of the min-max optimization problems, in [5] an optimization regarding the maximum stiffness and maximal workspace are performed. Firstly, the authors take into consideration each property independently, then perform a tradeoff between these two conflicting properties. The stiffness of a 3° of freedom (DOF) parallel robot is optimized in [6]. The authors propose the maximization of this property over a cubical usable workspace of the robot. Other examples present the optimization of other properties like the global conditioning index [7], the average inverse condition number [8], kinematic performance [9,10] or energy consumption [11]. In [12], a multi objective optimization of a linear Delta parallel robot is performed regarding the maximal dexterous workspace, best kinematic performances, best stiffness and best dynamic performances.

On the other hand, there are few published paper that take into consideration in the objective function the similarity between two workspaces. Examples as [13] or [14] propose the optimization of serial and parallel planar mechanism for prescribed workspace of regular shapes. Similar work is presented in [6], although the similarity between the designed workspace and the input into the optimization is not evaluated; other kinematic properties in the interior of the prescribed workspace are computed. Another recent paper proposes the optimization of the parameters of parallel robot in order to correlate its workspace to a prescribed regular one (a cylinder) and to maximize its conditioning index [15]. The aforementioned papers that treat the subject of optimization of robots usually take into consideration mostly several kinematic properties inside the workspace that have to be maximized or minimized. Moreover, the similarity between two workspaces has not been presented as an optimization problem in the case when the imposed workspace has irregular shape. Even if bounding two irregular spaces. Consequently, the research presented in this paper is focused on the optimization of a parallel robot to obtain a prescribed, irregular-shaped workspace.

Concerning the implementation of the optimization, Genetic Algorithms (GA) have been chosen taking into consideration their computational time, accuracy and efficiency [16]. The GA are evolutionary algorithms and are inspired by the genetics of the mechanisms from the natural systems. They preserve the information regarding the populations (solutions)