Techniques applied in design optimization of parallel manipulators

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Abstract— **There are some key advantages associated with parallel robots, which have warranted their continued research and wide application in both university laboratories and industry. To obtain a parallel manipulator with good properties, as customized by user specifications, the design parameters of a parallel manipulator must be optimized. The optimal design of the general parallel manipulator's kinematic parameters may be decomposed into two processes: structural synthesis and dimensional synthesis. Although both these processes will be described, the scope of this paper explores the dimensional synthesis aspect.**

Historical optimization methods adopted by researchers are discussed. This paper presents dimensional synthesis approaches based on performance requirements that have a potential to obtain almost all feasible design solutions that satisfy the requirements. The optimal design problem is a constrained nonlinear optimization problem with no explicit analytical expression. This makes the process of optimization a cumbersome and time-consuming endeavour, especially when the variables are diverse and objective functions are excessively complex. Thus, several techniques devised by researchers to solve the problem are reviewed in this paper.

Keywords-dimensional synthesis; optimization; parallel manipulators;

I. INTRODUCTION

Parallel mechanisms have been successfully used in many applications, a few of which include telescopes, position devices, medical, machine tool and flight simulators. These applications provide a convincing illustration of the main advantage of parallel robots namely, their load-carrying capacity, high stiffness, dexterity and accuracy. To obtain a parallel manipulator with good properties, as customized by user specifications, the design parameters of a parallel manipulator must be optimized.
The design of a robot can be decomposed into two main phases [1]:

- Structural synthesis: finding the general mechanical structure of the robot
- Geometric synthesis: determining the value of the geometric parameters involved in a given structure (here geometric parameters must be understood in loose sense, for example, mass and inertia may also be involved)

The advantage that serial robots have is that the number of possible mechanical architectures is relatively small. Some of these architectures have clear advantages in terms of performance compared to others for example; the workspace of a 3R structure is much larger than the workspace of a Cartesian robot of similar size.

Unfortunately no such rules exist for parallel robots, for which there are a large number of possible mechanical designs. Additionally, the performances of parallel robots are very sensitive to their geometric parameters. For example, it has been indicated in the case of the Gough platform, that the external stiffness over a given workspace can change by 700% for a change of only 10% of the platform radius. Consequently, structural synthesis cannot be dissociated from the geometric synthesis. In fact, it is deduced that a well-dimensioned manipulator of any structural type will generally surpass in performance, that of a poorly designed manipulator with a structure that may seem more appropriate for the task at hand. It is with this highlighted/indicated importance of the optimization issue that this paper takes up this discussion [1, 2].

The content of this paper can be summarized as follows; section II, the state of the art in dimensional synthesis is presented, section III, covers the efficient optimization techniques and section IV, concludes the paper.

II. DIMENSIONAL SYNTHESIS: STATE OF THE ART

Dimensional synthesis is broadly understood as the determination of the dimensions of parts (lengths, angles, thickness, etc.) necessary to create a mechanism that will effect a desired motion transformation or any parameter that will influence the robot behaviour and is needed for the manufacturing of the robot [3, 4].

In considering dimensional synthesis, it is recognised that it has two aspects, called approximate and exact. Exact synthesis is limited, since few arbitrary functions can be handled. For example, on the one side of a coin, it takes at least a six-bar linkage mechanism such as the Hart to generate a true straight line. On the other side of the coin there is a notable exception: only a trivial mechanism is required to describe a circle, while a four-bar is needed to produce circular arcs that are only approximate. Nevertheless, exact, or precision, synthesis is limited to certain functions, whereas approximate synthesis can accomplish the task within a limited range on almost any function.

There are generally two approaches- the geometric, or graphic, and the analytic, or algebraic. Geometry is, of course, analytical, but the term analytical has become associated with algebraic methods of computation in comparison with graphical constructions. In rather broad terms, it may be said that the geometric methods were developed by the German school, with emphasis planar linkages. The Russian effort, once heavily geometric, has now a strong bias toward the algebraic approach, well suited to spatial mechanisms. More recently in America, the principal developments have been in algebraic treatments, with the inclusion of spatial linkages.
The geometric methods can deliver quick and dependable solutions to a number of problems with reasonable accuracy. They give direct feeling for mechanical details, which are essential when reducing a given solution to hardware and which may be obtained on the drawing board without making use of sometimes unfamiliar or unavailable techniques of automatic computation. In the case of spatial mechanisms or when the requirements for accuracy are more demanding, geometric methods may, become cumbersome, lengthy, and undependable. For such problems, analytic methods, dependent on the use of automatic computation techniques, may yield practical and economical solution [4].

The literature reviewed indicates that Gosselin and Guillot whom were amongst the first to attempt to address the issue, presented an algorithm and synthesized a serial and a parallel manipulator with two degrees of freedom (DOFs) for prescribed workspaces. Merlet later in his monograph [2], named the problem "the exact synthesis of workspace". He introduced a numerical procedure to determine all possible geometries of 6-DOF Gough-type parallel manipulators whose workspace must include a desired one [5]. Boudreau and Gosselin [6], aimed to obtain a workspace as close as possible to a prescribed one by determining some parameters of the planar RPR using a genetic algorithm method. Laribi et al. [7], proposed a method combining genetic algorithm and fuzzy logic to obtain parameters for a prescribed cuboid workspace of the Delta robot. A numerical method was later presented in 2007 by Kosinska et al. [8] for determination of the parameters of Delta robot, for the prescribed cuboid and well-conditioned workspace. Hay et al. [9], proposed an algorithm to design the planar PR parameters for prescribed two-dimensional physically reachable output workspace. Huang et al. [10], presented an analytical approach to determine the actuated joint stroke of 6-PSS for a prescribed cylindrical workspace with the given orientation capability. Zhao et al. [11], proposed a method to minimize leg length of parallel manipulators for a desired cylindrical dexterous workspace. Here the least number method was exploited, of variables to optimize the leg length of a spatial parallel manipulator for the purpose of obtaining a desired dexterous workspace. A technique using planar quaternions was proposed by Murray et al. [12], for designing planar parallel manipulators with platforms capable of reaching any number of desired poses. Liu et al. [13], presented a geometrical method to determine the parameters of the linear Delta robot for desired workspace with prescribed local and global performance indices and later in 2006 Liu and Xin- Jun [14], presented a performance charts method to determine the parameters of the linear Delta robot for desired workspace with prescribed local and global performance indices.

III. REVIEW OF EFFICIENT OPTIMIZATION TECHNIQUES

Usually the design process is treated as an optimization problem. To each user specified performance requirement is associated a performance index whose value increases with its level of violation. These performance indices are summed in a weighted real-valued function called the cost function, which is a function of the geometric design parameters. A numerical optimization procedure is then used to find the parameters that minimize the cost function. Thus this approach leads to what is termed an optimal design [15-17]. Each approach presents with it's self some drawbacks, and this case these include: the determination and effect of weights in the cost function are difficult to incorporate and make the optimization process more complex, and the definition of the performance indices is not trivial. The main issues can be stated as:

- "The robustness of the design solution obtained with the cost function approach with respect to the uncertainties in the final design. Indeed the instantiation of a theoretical solution will always differ from the latter because of the manufacturing tolerances and other uncertainties that are inherent to a mechanical system,
- Performance requirements may be antagonistic (e.g. workspace and accuracy) and the optimal design approach only provides a compromise between these requirements that is difficult to master through the weights" [1].

An alternative to optimal design is referred to as appropriate design. In this process no optimization is considered but the objective is to ensure that desired requirements are satisfied. This is an approach based on the definition of the parameter space in which each dimension is associated with a design parameter. In turn the performance requirements are considered and the regions of the parameter space that correspond to robots satisfying these requirements are calculated. The design solution is then obtained for each individual requirement. Since values close to the boundary cannot be physically realized due to manufacturing tolerances, in practice, only an approximation of the regions is considered. Interval analysis was successfully employed for such a calculation in various applications [18, 19].
Of the two approaches the appropriate design approach is more complex to implement, but has the advantage of providing all design solutions, with the consequence that manufacturing tolerances may be taken into account to ensure that the real manipulator will also satisfy the desired requirements.

The optimal design problem is a multimodal constrained non linear optimization problem with no explicit expressions and the gradients and hessians are not readily evaluated, the common gradient-based algorithms are not suitable for this problem [20]. Lou et al. [21] adopted a direct search method, the controlled random search (CRS) technique, which was remarked reliable and robust. It is a global optimization method to find the optimal solution. The basic philosophy of the method is to select new points by random selection from normal probability distributions centered at the best previous value. The advantages of the CRS are ease of programming, inexpensive realization, insensitivity to type of criterion function, efficiency, flexibility and information provided and used. The Steward-Gough platform was employed as an example to demonstrate his design procedure. It can be seen that the algorithm converges very fast in the beginning, and converges very slow when close to the optimum.

Wang et al. [22] proposed a method based on the objective functions, but avoids non linear constrained problems. Applying this method, the optimal problem with nonlinear constraints is translated into two optimal problems without constraints such that the original problem, which was used to obtain optimal design parameters of a parallel manipulator whose workspace is as close as possible to the prescribed cylindrical dexterous workspace, is easily solved. Thus, the general non constraints optimal programming solver could be adopted to solve optimal problems. Then, the generalized pattern search algorithm (GPSA) in the genetic algorithm and direct search toolbox of Matlab [23, 24], an optimal design procedure is adopted to solve these problems. The advantage of the GPSA is convergence and the speed thereof. Thus, the set of optimal design parameters of the manipulator whose workspace is as close as possible to a prescribed regular dexterous workspace is obtained. But the method presented in [22] only considers a common linear delta robot.

A novel idea was presented in [24] based on [22] determined a set of optimal design parameters of a special structure of the linear Delta robot whose workspace is as close as possible to a prescribed rectangular dexterous workspace. A new concept of the distance between the best state of the parallel manipulator and the prescribed rectangular dexterous workspace is introduced, which is used to explain the reasonability of the parallel manipulator to the prescribed rectangular dexterous workspace.

[25] followed [22] in obtaining the optimal parameters whose workspace satisfied the prescribed rectangular and cylindrical dexterous workspace of another linear delta robot. While [26] went on to employ the same method into a Y-Star robot with the aim to obtain the optimal parameters satisfied the prescribed cylindrical dexterous workspace.

The nature of a significant number of practical optimum design problems is that of mixed continuous discrete variables, and discontinuous and non-convex design spaces. In such a case, the application of standard nonlinear programming techniques tends to be inefficient, computationally expensive, and in most cases, find a relative optimum that is closest to the starting point. Artificial intelligence (AI) techniques have emerged as suitable candidates for solving such problems, and in most cases they can find the global optimum solution with a high probability.

These methods are conceptually different from the traditional mathematical programming techniques and are labelled as modern or non-traditional methods of optimization. Most of these methods are based on certain characteristics and behaviour of biological, molecular, swarm of insects, and neurological systems. These methods include: genetic algorithms, simulated annealing, particle swarm, ant colony, fuzzy optimization and neural networks [27].

AI techniques are emerging as popular methods for the solution of complex engineering problems and mostly require only the function values and not the derivatives. Genetic algorithms are based on the principles of natural genetics and natural selection, while simulated annealing is based on the simulation of thermal annealing of critically heated solids. They are both stochastic methods that can find the global minimum with a high probability and are naturally applicable for the solution of discrete optimization problems. Particle swarm optimization is based on the behaviour of a colony of living things, such as a swarm of insects, a flock of birds, or a school of fish. Ant colony optimization is based on the cooperative behaviour of real ant colonies, which are able to find the shortest path from their nest to a food source. Fuzzy optimization methods have been developed for solving problems in which, the objective function, constraints, and the design data are known only in vague and linguistic terms. In neural network based methods, the problem is modelled as a network consisting of several neurons and trained to solve the optimization problem efficiently [27].

Some innovative optimal solvers, which are said to employ efficient methodologies have been developed to improve search efficiency [20] and applied to parallel manipulators are discussed in what follows.

An optimal design procedure which excluded any nonlinear problems was proposed by Liu et al.[13, 14]. This method employs the performance chart, a tool which is widely used in the classical design and most design manuals. To present the performance chart in a finite space, he proposed a method to normalize the involved design parameters at first [28]. The solution of the optimal design is such that the consumer can know how optimal the result is due it being very clear and intuitionistic. One of the limiting factors is that the workspace must be obtained geometrically, which adds a degree of complexity in dealing with the various constraints and interfaces of joints and links. Another limiting factor is that the method only considers a common linear delta robot which may not be suitable for the general parallel manipulator.

IV. CONCLUSION

Performance optimization, a challenging task that it is, is an integral issue for more extensive industrial applications of parallel manipulators, in a niche market has been identified. By adjusting the architectural and behavioural parameters, the optimal performance indices of any parallel manipulator can be enhanced. Several techniques have been developed by researchers, in addressing the issue of optimization, are reviewed and discussed in the above sections.

The unrelenting enhancement in computing power has led to numerical optimization techniques becoming more and more popular in many fields, including robotics. Most current optimization algorithms can be broadly classified as either deterministic or stochastic methods [29]. The methods discussed in this work are in general for nonlinear optimization problems, since these are the sorts of problems encountered in the mechanism synthesis field.

Deterministic techniques use knowledge of the local topography of the objective function to move towards the optimum design. Such methods include classical optimization techniques, line search methods, gradient based methods, the simplex method and moving asymptotes. Although many such methods exist, the discussion in this study has been limited to techniques which have direct relevance to parallel manipulators.

This paper serves as a guideline to researchers on efficient optimization techniques as pertaining to parallel manipulators.

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