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A generic method to optimize a redundant serial robotic manipulator's structure

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ABSTRACT

In this paper, an optimization method for a redundant serial robotic manipulator's structure is proposed in order to improve their performance. Optimization was considered in terms of kinematics using the proposed objective function and the non-linear Levenberg-Marquardt algorithm for multi-variate optimization. Range limits of the joints, bounds of the design parameters, and a constrained workspace are enforced in the proposed method. A desired manipulator can be optimized to cover the required task points using dimensional synthesis. This approach effectively optimizes the link lengths of the manipulator and minimizes the position and orientation errors of the tool center point. A commercial heavy-duty hydraulic, underground tunneling manipulator was used to demonstrate the capability of the proposed optimization method. The obtained results encourage the use of the proposed optimization method in automated construction applications, such as underground tunneling, where the confined environment and the required task add challenges in the design of task-based robotic manipulators.

1. Introduction

Construction project must always battle against time and cost. One has to get the project right and get it right from the start. This requires very deep knowledge in construction but also a range of equipment that can handle the required tasks. Particularly, tunneling construction involves very demanding projects with confined workspaces. Therefore, the appropriate structural design of manipulators plays an important role in designing the optimal manipulator.

Most commonly, industrial robotic manipulators with six degree of freedom and spherical wrists are designed to achieve the desired payload while maximizing the robot's workspace envelope. In more advanced design scenarios, the robot's total orientation workspace can be specified as the range of the end-effector's rotation angles inside a bounded workspace [1]. This type of design can be classified as general purpose design. Although using a general purpose design is generally acceptable, it does not guarantee the optimal design for task execution. Therefore, task-based optimization is preferred when a task is predefined.

The task-based optimization or synthesis of a robotic manipulator consists of finding a set of manipulator design parameters so that the required task points and kinematic requirements are fulfilled. The kinematic requirements, such as a constrained workspace, design parameter limits and joint limits, are task specifications that affect the kinematic structure of the robotic manipulator.

The most important requirement of the manipulator is the ability to reach to the desired task points. For example, in tunnel construction, the purpose of a drill plan is to describe the set descriptive poses that must be reached. This may not be used by the customer in a single drilling phase. Instead, it may contain selected drill plans combined into a single set of task points. Other priorities include obstacle avoidance, singularity avoidance, manipulator dexterity and several other objectives that affect the kinematic design of manipulators directly or indirectly.

Comprehensive studies have been conducted on the kinematic synthesis of serial robotic manipulators [2–11]. A classic approach to task-based dimensional synthesis is to create objective and constraint functions and then sum them to form a cost function, which can be minimized to find an optimal solution [2–4]. Constraint functions can be weighted to address the solution in the specified direction. Although previous studies have shown how different optimization approaches can be used to solve task-based dimensional synthesis problems, they are limited and solve only a part of our optimization problem. For example, [5–7] focus on non-redundant manipulators, and some works concentrate the optimization of serial manipulators with only three joints [4,6,8]. Furthermore, some works are restricted and optimize the

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manipulator's structure based on end-effector's position rather than on both position and orientation [4,9]. Usually, there is no explanation of where the task points came from. Further, the number of task points is often limited to only a few points [2,5,9]. As a result, no comprehensive real-world scale study appears to exist.

In spite of previous studies, the task-based optimization of an arbitrary manipulator's structures with practical relevance has yet to be achieved. Hence, additional studies of the task-based optimization of arbitrary manipulators to find the appropriate values for the design parameters, the base frame, and the joint values are needed. Typically, this type of optimization problem required several hundreds of parameters to be optimized. Therefore, the aim of this paper is to extend the aforementioned works to cover more general serial manipulators optimization with practical relevance for construction manipulators. The proposed optimization method can handle non-redundant and redundant manipulators. Furthermore, it can handle both revolute and prismatic joints and n-dimensional task spaces as well as end effector position and orientation. In addition, the proposed method can be used to optimize hundreds of parameters efficiently, and the number of parameters to be optimized is not restricted by the proposed method.

In this paper, we propose an optimization method that takes into account not only the desired task points but also practical design constraints for given task points, including most important constraints, such as the available confined working envelope and joint ranges. The topology of the tunnel construction manipulator used in this case study is proven by construction customers to be suitable for tunnel construction. Therefore, a change in the manipulator's topology was not necessary in this study. Instead, the dimensions of the existing manipulator were optimized to enhance the performance and profitability of the manipulator.

Studied tunnel drilling patterns consist of multiple task points where several real drill plans are combined into a single set of task points. This real customer application requires a long-reach manipulator (10–15 m) due to the desired tunnel size. Therefore, a manipulator with at least one prismatic joint is of interest. Our results indicate that this method is effective in optimizing the manipulator's dimensions compared to the original manipulator's design according to the selected performance measures.

We have organized the rest of this paper as follows. In Section 2, the kinematic synthesis process is described according to the task specification. In Section 3, the dimensional synthesis method based on selectively damped least squares is described with optimization constraints and initial design parameters. The proposed kinematic synthesis method was applied to a case study; the results are given in Section 4, and the conclusions are given in Section 5.

2. Kinematic synthesis

In general, kinematic synthesis can be divided into two separate types: topology synthesis and dimensional synthesis. Topology synthesis involves determining the structure of a device, whereas dimensional synthesis is devoted to determining the dimensions of a device. The synthesis process begins with defining the task that the manipulator's structure should be able to fulfill. This step is preferably performed with the customer to maximize the benefit the machine will bring him or her. For example, if the machine must be carefully repositioned before starting a new work cycle, it may be desirable to reach a certain number of goal points before repositioning is needed. In general, the task consists of several poses that need to be reached by the manipulator together with a tool attached to it. Each of these task points can be expressed with a homogeneous transformation matrix, which is described as follows:

$$\mathbf{T}_{tcp}^{w} = \begin{bmatrix} \mathbf{n}_{tcp}^{w} & \mathbf{s}_{tcp}^{w} & \mathbf{a}_{tcp}^{w} & \mathbf{p}_{tcp}^{w} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

where $\mathbf{n}_{tcp}$, $\mathbf{s}_{tcp}$, and $\mathbf{a}_{tcp}$ are the unit vectors of a frame attached to the end effector and $\mathbf{p}_{tcp}$ is the position vector of the origin of the frame with respect to the origin of the world frame. In addition to locations and orientations given with the required degrees of freedom, tasks may also include other required attributes, such as a required force output or structural stiffness.

Usually, the number and type of joints are given as input parameters for kinematic synthesis. In some methods, the angles between two consecutive links can be design parameters, and the optimization method decides these angles. For example, Singla et al. [2] optimized redundant serial manipulators for cluttered environments, and Ouezdou et al. [11] optimized manipulators with task specifications. They defined the number of joints, type and order of the joints, and then used the optimization process to find the optimal link length and joint locations. This type of optimization is preferred for cluttered environments where it is mandatory to use complicated snake-like manipulators. For example, in [2], 8–10 joints were needed to achieve satisfactory results. In applications where the environment is not cluttered, it is preferable to keep the design as simple as possible and the number of joints as small as possible. With twist angles fixed between two consecutive links, it is possible to optimize simple structures, which makes it easier to produce than complex structures. If the joints of the manipulator have to be hydraulic due to high torque requirements, the most desirable hydraulic joint is driven by a hydraulic cylinder, which is more cost-effective and lighter in weight than hydraulic motors. Therefore, it is profitable to use hydraulic cylinders whenever possible. Hydraulic cylinders are much easier to implement if the twist angle between the joints is multiple with 90 °.

2.1. Topology synthesis

Topology synthesis involves determining the structure of a device, excluding link lengths, from the task description. The word *structure* is used to describe the number, type, and arrangement of joints and the links connected by these joints. Ideally, topology synthesis results in an optimal topology for the task, and this topology is the subjected to dimensional synthesis to determine link lengths (see Section 2.2).

There is no general approach for the topology synthesis of open-chain serial manipulators. Graph theory [12] is widely used in research involving topology synthesis, but most of these studies are related to closed-chain kinematic structures [13,14]. For open-chain kinematic structures, a logical approach using existing knowledge is appropriate for topology synthesis.

2.2. Dimensional synthesis

A classic approach for dimensional synthesis begins with assigning weight factors for several criteria and then totalling them to form a cost function, which can be then minimized to find an optimal solution [3,4]. The multi-variable, multi-constraint and multi-objective aspects of the problem are further discussed in [10]. Other methods include stochastic algorithms, distributed optimization techniques [11] and parameter space approaches, which are used for the parallel Gough platform in [15].

The augmented Lagrangian method is a constrained optimization method [2]. A pure penalty function method penalizes an objective function in order to discourage constraint violation, typically using a large penalty parameter. This causes a poor rate of convergence, since the Hessian of the Lagrangian becomes ill-conditioned. In the augmented Lagrangian method, the Lagrangian is combined with a modest penalty term. In [2], the augmented Lagrangian method was used, and it proved to be efficient and robust for the synthesis of serial redundant manipulators with obstacle avoidance. In that research, the authors achieved synthesis with 6-, 8-, and 10-joint manipulators.

The genetic algorithm method can be used to optimize a multi-objective cost function that contains many local minimum points. Barissi