Applied Soft Computing 13 (2013) 899–910

Contents lists available at SciVerse ScienceDirect

Applied Soft Computing

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

Revolute manipulator workspace optimization: A comparative study

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ARTICLE INFO

Article history:
Received 7 August 2011
Received in revised form 11 July 2012
Accepted 4 September 2012
Available online 27 September 2012

Keywords:
Robot manipulator
Revolute
Optimization
Workspace volume
Bacteria foraging

ABSTRACT

Robotic manipulators with three revolute families of positional configurations are very common in the industrial robots. The capability of a robot largely depends on the workspace of the manipulator apart from other parameters. In this work, an evolutionary optimization algorithm based on foraging behavior of *Escherichia coli* bacteria present in human intestine is utilized to optimize the workspace volume of a 3R manipulator. The proposed optimization method is subjected to some modifications for faster convergence than the original algorithm. Further, the method is also very useful in optimization problems in a highly constrained environment such as the robot workspace optimization. The test results are compared with standard results available using other optimization algorithms such as Differential Evolution, Genetic Algorithm and Particle Swarm Optimization. In addition, this work extends the application of the proposed algorithm to two different industrial robots. An important implication of this paper is that the present algorithm is found to be superior to other methods in terms of computational efficiency.

1. Introduction

There is long-standing interest in the design of robot manipulators. Growing importance of revolute manipulators in manufacturing has made its optimal design, a real challenge. Little success has been achieved in this area because of some difficulties associated with geometrical constraints and complexity of modeling it. A robot manipulator structure can be subdivided into a regional structure and orientation structure as proposed by Kucuk and Bingul [1]. On the one hand, the regional structure consists of the arm, which moves the end-effectors to a desired position in the workspace of the robot manipulator. On the other hand, the orientation structure comprises of the links that rotate the end-effectors to a desired orientation in the workspace. In this study, only the regional structure of the robot manipulator is examined keeping the orientation structure fixed. The size and shape of the workspace depends on both the coordinate geometry of the robot arm, and the number of degrees of freedom it has. Some workspaces are quite flat, confined almost entirely to one horizontal plane. However, some of the types are cylindrical and in some cases spherical as proposed by Kucuk and Bingul [1]. While choosing a robot arm for a certain industrial purpose, it is important to have a larger workspace to encompass all the points that the robot end-effector needs to reach. On the contrary; it is wasteful to use a robot arm with a workspace much larger than the volume required for the particular job.

Further, there is a close relationship between the kinematics performance and geometric design of robot manipulators. Because of this, several kinematics-related criteria are suggested for designing a well-conditioned robot manipulator having optimum workspace. The geometric design of a manipulator is based on workspace volume as the workspace describes the fundamental features of the manipulator. Under these circumstances, it is necessary to determine the workspace volume with high degree of accuracy.

In the recent past various researchers have approached the workspace formulation and optimization problem with different solution methodologies, which are given as follows:

1. Algebraic and Geometric formulation [2–7,9–13]
2. Heuristic oriented [8]
3. Mono-objective and Multi-objective optimization [17–22].

In the past, many researchers have given great attention to address the workspace representation and its evaluation methodologies, for analysis and design of manipulators. Gupta and Roth [9] have presented some of the valuable concepts regarding the workspaces of manipulators probing into details of the primary and secondary workspaces. Illustrated through examples, the focus of discussion mainly covers the affects of three mutually intersecting axes and that of the hand size. Similarly, studies by Freudenstein and Primrose [10] analyze the workspace of a three-axis,

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http://dx.doi.org/10.1016/j.asoc.2012.09.009

Nomenclature

d_j	Link off-set
θ_i	Joint rotation angle
α_j	Link rotation angle
H	Reference point
H_i	Reference point coordinate in *i*th frame
T^i_{i-1}	Transformation matrices of a reference on the former
T (superscript)	Transpose
r	Radial reach
z	Axial reach
r_{max} and r_{min}	Maximum and minimum radial reach
z_{max} z_{min}	Maximum and minimum axial reach
a^u_i	Maximum link length
d^u_j	Maximum link off set
A_T	Total area
V	Workspace volume
r_g	Center of mass of cross-section area
L_{max}	Maximum total link length
W(H)	Workspace region

turning-pair connected robot arm of general proportions, in terms of the volume swept out by the surface of a skew torus rotating about an offset axis in space. The algebraic geometry of this configuration was then utilized in determining the workspace characteristics. Ceccarelli [11] developed a method for the synthesis of a three revolute (3R) manipulators whose structure had minimum size encumbrances and workspace with prescribed constraints. For this work, Sequential Quadratic Programming (SQP) optimization technique was used in the proposed model to optimize the workspace volume which is very much useful to investigate the effect of link size for design purpose. The algebraic formulation can also be manipulated to deduce analytical synthesis algorithms. In the sequel by the same author [12], an algebraic formulation was proposed to describe the workspace boundary of general N-R revolute open chain manipulators. The workspace was formulated from the envelope of a torus family that was traced by the parallel circles cut in the boundary of a revolving hyper-ring. In continuation to [12], an analytical procedure was also proposed in [14] for determining the workspace boundary of general telescopic manipulators. The algorithm provides an algebraic formulation using the Theory of Envelopes.

Wenger [15] provided tools and guidelines for designers of novel manipulators so as to facilitate adjustment of the kinematic parameters for desired kinematic properties during the synthesis process. The geometric design problem of serial-link robot manipulators with 3R joints was proposed by Lee et al. [16] and the problem was solved using a polynomial homotopy continuation method. Three spatial positions and orientations were defined and the dimensions of the geometric parameters of the 3-R manipulator were computed so as to place the manipulator's end-effectors at these three pre-defined locations. Moreover, Lanni et al. [17] formulated the optimum design of 3R manipulators by using an algebraic formulation of workspace boundary. The authors developed a multi-objective optimization approach by simultaneously considering manipulator size and the workspace volume in the objective function. Then, SQP and simulated annealing (SA) optimization techniques were used to optimize the workspace volume. However, it was observed that the link offset was a less sensitive parameter in optimal design of manipulator.

Saramago et al. [18] formulated a general analytical condition to determine the cusp point on the internal and external boundaries of workspace. Similarly, Ceccarelli and Lanni [19], suitably formulated the workspace of a 3R manipulator, where the optimal design of the manipulator was expressed as multi-objective optimization problem by taking the workspace volume and robot dimensions as the two objectives, and the given workspace limits as constraints. The optimal design was successfully optimized by using SQP. It was also reported that the twist angles are very influential in the design process and that the initialized values of manipulator parameters for optimization play an important role in the final solution. Bergamaschi et al. [20,21] presented a suitable algebraic formulation of workspace volume and identified the optimum values of geometric parameters of manipulator. The optimization problem in [21] was formulated with workspace volume as objective function and with the help of SQP, the optimum geometrical dimensions of the manipulator were determined. The major disadvantages in the case of conventional optimization techniques are that, they require their objective functions in terms of control variables and also that they need local information for exploration of these variables. In addition, these techniques have tendency to converge at local optimum values. To overcome above shortcomings, uses of evolutionary-based techniques are envisaged.

Bergamaschi et al. [22] formulated an optimization problem using workspace as objective function and solved the problem by applying evolutionary optimization techniques. A comparison of four optimization techniques, i.e., SQP, Genetic algorithm (GA), Differential evolution (DE) and Particle Swarm Optimization (PSO) was presented by the authors. In the present work attempt is made to optimize workspace volume of manipulators using a novel optimization technique based on foraging behavior of *Escherichia coli* bacteria present in human intestine, known as bacteria foraging algorithm (BFA). Moreover, all the possible constraints such as regularity constraints, inequality constraints and limiting constraints are considered, both separately and simultaneously.

The optimization problem is formulated taking into account the algebraic formulation described in [22] and solved by using BFA. In addition to the theory, we present workspace volume from numerical simulations of diverse cases as obtained by proposed BFA and the results are compared with those reported in [22] using SQP, DE, GA, PSO and BFA by Passino [25]. Workspace volume optimization using proposed BFA and avoidance of side constraints violation are the novelty of the present work.

2. A workspace formulation of 3r manipulator

Manipulator arms are the structural chains, which aim to let the end-effectors reach positions in the space. Therefore manipulator workspace is characterized by radial and axial reaches. Workspace *W(H)* can be defined as the region of points that can be reached by a reference point *H* on the end-effectors 0 of a manipulator. A workspace point coordinate can be described the *Z*-axis of the base and along a radial direction orthogonal to the *Z*-axis, respectively. The base frame can be fixed to the base of a manipulator with the *Z*-axis coinciding with first joint axis, and the *X*-axis coinciding with the home configuration of the X_1-axis, which is fixed on the first link length a_1 with the D–H (Denavit and Hartenberg [29]) description of a manipulator as shown in Fig. 1. The geometrical parameters of a general 3R manipulator as per D–H Algorithm are: the link length $a_i \neq 0$ (i = 1, 2, 3), the link offsets d_i (i = 2, 3), and the twist angles α_i (i = 1,2). The parameter d_1 may not be considered in a design algorithm since it shifts the workspace up and down only and therefore it does not affect a workspace evaluation. The joint angles θ_i (i = 1, 2, 3) are defined as the angles between two consecutive *X*-axes.