24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
Construction Automation Group, I.I.T. Madras

A MULTICRITERIA APPROACH FOR THE OPTIMAL DESIGN OF 2 DOF PARALLEL ROBOTS USED IN CONSTRUCTION APPLICATIONS

Stan Sergiu-Dan
Dept. of Mechanics and Programming
C. Daicoviciu nr. 15, 400020, Cluj-Napoca, Romania
sergiustan@ieee.org

Vistrian Mătieş and Radu Bălan
Dept. of Mechatronics
C. Daicoviciu nr. 15, 400020, Cluj-Napoca, Romania
{matiesvistrian, radubalan}@yahoo.com

ABSTRACT

Parallel robots have been used in a large number of applications ranging from astronomy to flight simulators and are becoming increasingly popular in the field of construction industry. This paper is aimed at presenting a study on the optimization of the BIGLIDE and BIPOD parallel robots, which comprises two-degree-of-freedom (DOF) parallel robots with constant and variable struts. The robot workspace is characterized and the inverse kinematics equation is obtained. In the paper, design optimization is implemented with Genetic Algorithms (GA) for optimization considering transmission quality index, design space and workspace. Here, intended to show the advantages of using the GA, we applied it to a multicriteria optimization problem of 2 DOF parallel robots. Genetic algorithms (GA) are so far generally the best and most robust kind of evolutionary algorithms. A GA has a number of advantages. It can quickly scan a vast solution set. Bad proposals do not affect the end solution negatively as they are simply discarded. The obtained results have shown that the use of GA in such kind of optimization problem enhances the quality of the optimization outcome, providing a better and more realistic support for the decision maker. Considering its high load capacity and geometrical dexterity, the system is appropriate for maintenance, building construction, and cleaning of large and dangerous structures.

KEYWORDS

Optimal Design, Parallel Robots, Genetic Algorithms

1. INTRODUCTION

Several papers have dealt with parallel robots to optimize performances [14]. However, many of these are limited to only one performance optimization. For example, various methods to determine workspace of a parallel robot have been proposed using geometric or numerical approaches. Early investigations of robot workspace were reported by Gosselin [1], Merlet [2], Kumar and Waldron [3], Tsai and Soni [4], Gupta and Roth [5], Sugimoto and Duffy [6],Gupta [7], and Davidson and Hunt [8]. The consideration of joint limits in the study of the robot workspaces was presented by Delmas and Bidard (1995). Other works that have dealt with robot workspace are reported by Agrawal [9], Gosselin and Angeles [10], Cecarelli [11]. Agrawal [12] determined the workspace of in-parallel manipulator system using a different concept namely, when a point is at its workspace boundary, it does not have a velocity component along the outward normal to the boundary. Configurations are determined in which the velocity of the end-effector satisfies this property. Pernkopf and Husty [13] presented an algorithm to compute the reachable workspace of a spatial

Stewart Gough-Platform with planar base and platform (SGPP) taking into account active and passive joint limits. Stan [14] presented a genetic algorithm approach for multi-criteria optimization of PKM. Most of the numerical methods to determine workspace of parallel manipulators rest on the discretization of the pose parameters in order to determine the workspace boundary [15, 16]. Other authors proposed to determine the workspace by using optimization [14]. Numerical methods for determining the workspace of the parallel robots have been developed in the recent years. Exact computation of the workspace and its boundary is of significant importance because of its impact on robot design, robot placement in an environment, and robot dexterity.

The objective of this paper is to propose an optimization method for planar mini parallel robots that combines performance evaluation criteria related to the following robot characteristics: workspace, design space and transmission quality index. Furthermore, a genetic algorithm is proposed as the principle optimization tool. The success of this type of algorithm for parallel robots optimization has been demonstrated in various papers [14].

2. DOF MINI PARALLEL ROBOTS

Geometrical description of the parallel robots

Two general planar mini parallel robots with two degrees of freedom activated by prismatic joints are shown in Fig. 1 and Fig. 2.

There are a wide range of parallel robots that have been developed but they can be divided into two main groups:

- Type 1) parallel robots with variable length struts;
- Type 2) parallel robots with constant length struts;

Kinematic analysis

Robot kinematics deal with the study of the robot motion as constrained by the geometry of the links. Typically, the study of the robot kinematics is divided into two parts, inverse kinematics and forward (or direct) kinematics.

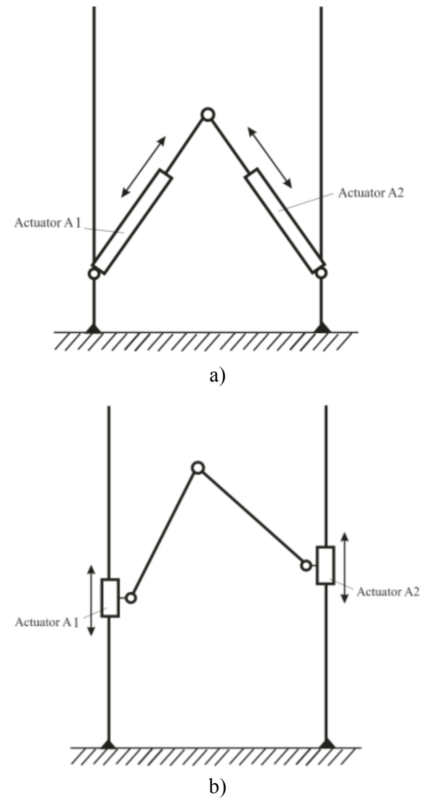

Figure 1.a) Variable Length Struts Parallel Robot b) Constant Length Struts Parallel Robot

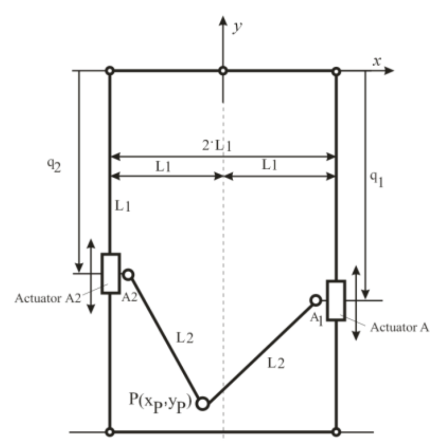

Figure 2 The General Kinematic Scheme of a PRRRP Mini Parallel Robot

The kinematics relation between **x** and **q** of these 2 DOF mini parallel robots can be expressed solving the following equation: f(**x**, **q**) =0.

Then the inverse kinematics problem of the parallel robot from Fig. 2 a) can be solved by writing the following equations:

$$q_1 = y_P \pm \sqrt{L_2^2 - (x_p - L_1)^2}\,;$$
$$q_2 = y_P \pm \sqrt{L_2^2 - (x_p + L_1)^2} \qquad (1)$$

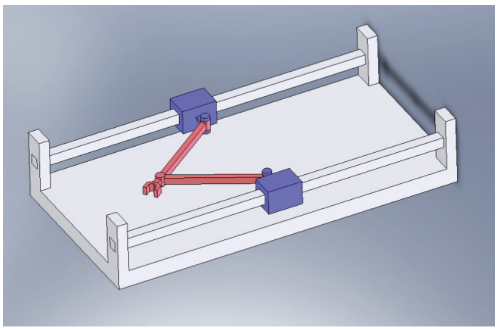

Figure 3 CAD Model of the Parallel Robot

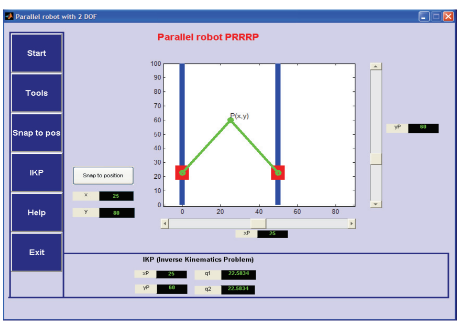

Figure 4 Robot Configuration for X_P=25 mm Y_P=60 mm

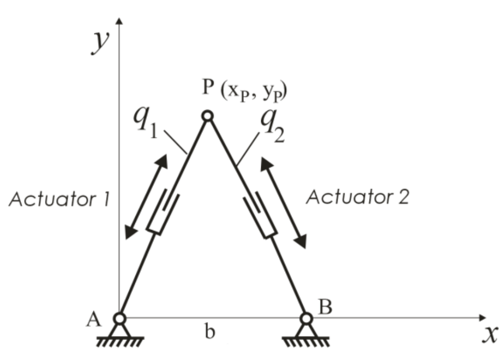

Figure 5 The General Kinematic Scheme of a RPRPR Mini Parallel Robot

Then the inverse kinematics problem of the parallel robot from Fig. 2 b) can be solved by writing the following equations:

$$q_1 = \sqrt{x_P^2 + y_P^2}\,;\, q_2 = \sqrt{(b - x_P)^2 + y_P^2} \qquad (2)$$

The forward and the inverse kinematics problems were solved under the MATLAB environment and it contains a user friendly graphical interface.

3. WORKSPACE DETERMINATION AND OPTIMIZATION

Workspace evaluation

The workspace is one of the most important kinematics properties of manipulators, even by practical viewpoint because of its impact on manipulator design and location in a workcell [17]. A general numerical evaluation of the workspace can be deduced by formulating a suitable binary representation of a cross-section in the taskspace. Other authors proposed to determine the workspace by using optimization [14].

The following presents the main factors affecting workspace. For ease of comparison a cubic working envelope with a common contour length is used together with a machine size that is calculated from the maximum required strut length.

The working envelope with variable and constant length struts

In this section, the workspace of the proposed robots will be discussed systematically. It is very important to analyze the area and the shape of workspace for parameters given robot in the context of industrial application. The workspace is primarily limited by the boundary of solvability of inverse kinematics. Then the workspace is limited by the reachable extent of drives and joints, occurrence of singularities and by the link and platform collisions. The mechanisms PRRRP and RPRPR realize a wide workspace as well as high-speed. Analysis, visualization of workspace is an important aspect of performance analysis. A numerical algorithm to generate reachable workspace of parallel manipulators is introduced.

Optimization results for RPRPR mini parallel robot

The design of the robot can be made based on any particular criterion. The paper presents a genetic algorithm approach for workspace optimization of Bipod mini robot. For simplicity of the optimization calculus a symmetric design of the structure was chosen. In order to choose the robot dimensions b, q_{1min}, q_{1max}, q_{2min}, q_{2max}, we need to define a performance index to be maximized. The chosen performance index is W (workspace) and T (transmission quality index). An objective function is defined and used in optimization. It is noted as in Eq. (2), and corresponds to the optimal workspace and transmission quality index. We can formalize our design optimization problem as the following:

$$ObjFun=W+T \tag{3}$$

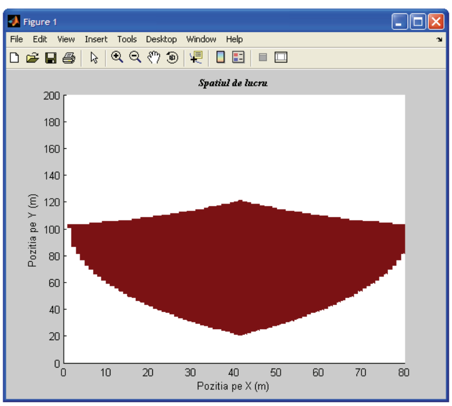

Figure 6 Workspace for the Planar 2 DOF Mini Parallel

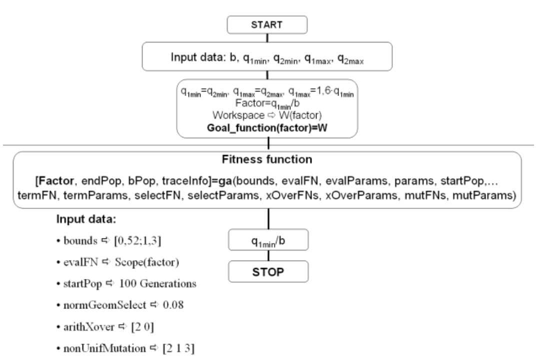

Figure 7 Flowchart of the Optimization Algorithm with GAOT (Genetic Algorithm Optimization Toolbox)

Optimization problem is formulated as follows: the objective is to evaluate optimal link lengths which maximize (3). The design variables or the optimization factor is the ratios of the minimum link lengths to the base link length b, and they are defined by:

$$q_{1min}/b \tag{4}$$

Constraints to the design variables are:

$$0,52<q_{1min}/b<1,35 \tag{5}$$

$$q_{1min}=q_{2min},\quad q_{1max}=q_{2max},\quad q_{1max}=1,6q_{1min},\quad q_{2max}=1,6q_{2min} \tag{6}$$

For this example the lower limit of the constraint was chosen to fulfill the condition $q_{1min}\geq b/2$ that means the minimum stroke of the actuators to have a value greater than the half of the distance between them in order to have a workspace only in the upper region. For simplicity of the optimization calculus the upper bound was chosen $q_{1min}\leq 1,35b$. During optimization process using genetic algorithm it was used the following GA parameters, presented in Table 1. A genetic algorithm (GA) is used because its robustness and good convergence properties. The GA approach has the clear advantage over conventional optimization approaches in that it allows a number of solutions to be examined in a single design cycle. The traditional methods searches optimal points from point to point, and are easy to fall into local optimal point. Using a population size of 50, the GA was run for 100 generations. A list of the best 50 individuals was continually maintained during the execution of the GA, allowing the final selection of solution to be made from the best structures found by the GA over all generations.

Table 1 GA Parameters

Generations	100
Crossover rate	0.08
Mutation rate	0.005
Population	50

We performed a kinematic optimization in such a way to maximize the objective function. It is noticed that optimization result for Bipod when the maximum workspace of the 2 DOF planar parallel robot is obtained for $q_{1\min}/b$=1,35. The used dimensions for the 2 DOF parallel robot were: q_{1min}=80 mm, q_{1max}=130 mm, q_{2min}=80 mm,

q_{2max}=130 mm, b=60 mm. Maximum workspace of the mini parallel robot was found to be W= 4693,33 mm^2.There have been obtained different values of the parameter optimization (q_1/b) for different objective functions. The following table presents the results of optimization for different goal functions. W_1 and W_2 are the weight factors.

If an elitist GA is used, the best individual of the previous generation is kept and compared to the best individual of the new one. If the performance of the previous generation's best individual is found to be superior, it is passed on to the next generation instead of the current best individual

Table 2 Results of Optimization for Different Goal Functions

	Method	GAOT Toolbox MATLAB
Goal functions	$Z=W_1 \cdot T+W_2 \cdot W$, W_1=0,7 and W_2=0,3	q_1/b = 0.92
	Z=W1·T+W2·W, W_1=0,3 and W_2=0,7	q_1/b= 1.13
	$Z= W_1 \cdot T$, W_1=1 and W_2=0	q_1/b=0.71
	$Z=W_2 \cdot W$, W_1=0 and W_2=1	q_1/b=1.3

The results show that GA can determine the architectural parameters of the robot that provide an optimized workspace. Since the workspace of a parallel robot is far from being intuitive, the method developed should be very useful as a design tool.

Table 3 Results of Optimization for Different Goal Functions

	Method	GAOT Toolbox MATLAB
Goal functions	$Z=W_1 \cdot T+W_2 \cdot W$, W_1=0,7 and W_2=0,3	*L2* = 1.1
	$Z=W_1 \cdot T+W_2 \cdot W$, W_1=0,3 and W_2=0,7	*L2*= 1.1556
	$Z= W_1 \cdot T$, W_1=1 and W_2=0	*L2*=1
	$Z=W_2 \cdot W$, W_1=0 and W_2=1	*L2*=1.2

However, in practice, optimization of the robot geometrical parameters should not be performed only in terms of workspace maximization. Some parts of the workspace are more useful considering a specific application. Indeed, the advantage of a bigger workspace can be completely lost if it leads to new collision in parts of it which are absolutely needed in the application. However, it's not the case of the presented structure.

Optimization results for PRRRP mini parallel robot

An objective function is defined and used in optimization. Objective function contains workspace and transmission quality index. Optimization parameter was chosen as the link length L2. The constraints was established as 1<L2<1.2. After performing the optimization the following results were obtained:

Based on the presented optimization methodology we can conclude that the optimum design and performance evaluation of the mini parallel robot is the key issue for an efficient use of mini parallel robots. This is a very complex task and in this paper was proposed a framework for the optimum design considering basic characteristics of workspace, singularities and isotropy.

4. CONCLUSION

The fundamental guidelines for genetic algorithm to optimal design of micro parallel robots have been introduced. It is concluded that with three basic generators selection, crossover and mutation genetic algorithm could search the optimum solution or near-optimal solution to a complex optimization problem of micro parallel robots. In the paper, design optimization is implemented with Genetic Algorithms (GA) for optimization considering transmission quality index, design space and workspace. Genetic algorithms (GA) are so far generally the best and most robust kind of evolutionary algorithms. A GA has a number of advantages. It can quickly scan a vast solution set. Bad proposals do not affect the end solution negatively as they are simply discarded. The obtained results have shown that the use of GA in such kind of optimization problem enhances the quality of the optimization outcome, providing a better and more realistic support for the decision maker. Considering its high load capacity and geometrical dexterity, the system is appropriate for maintenance, building construction, and cleaning of large and dangerous structures.

5. REFERENCES

[1] C. Gosselin. "Determination of the workspace of 6-d.o.f. parallel manipulators". ASME

Journal of Mechanical Design, 112:331–336, 1990.

[2] J. P. Merlet. "Determination of the orientation workspace of parallel manipulators". Journal of intelligent and robotic systems, 13:143–160, 1995.

[3] A. Kumar, KJ. Waldron. "The workspace of mechanical manipulators". ASME J. Mech. Des. 1981; 103:665-672.

[4] YC. Tsai, AH. Soni. "Accessible region and synthesis of robot arm". ASME J. Mech Des. 1981, 103: 803-811.

[5] KG. Gupta, Roth B., "Design considerations for manipulator workspace". ASME J. Mech. Des. 1982, 104(4), 704-711.

[6] K. Sugimoto, Duffy J, Hunt KH, "Special configurations of spatial mechanisms and robot arms". Mech Mach Theory 1982, 117(2); 119-132.

[7] JK. Davidson, KH. Hunt, "Rigid body location and robot workspace: some alternative manipulator forms". ASME J. Mech. Transmissions Automat Des 1987, 109(2); 224-232.

[8] SK. Agrawal, "Workspace boundaries of in-parallel manipulator systems". Int. J. Robotics Automat 1990, 6(3) 281-290.

[9] C. Gosselin, Angeles J. "Singularities analysis of closed loop kinematic chains". IEEE Trans Robotics Automat 1990; 6(3) 281-290.

[10] M. Cecarelli, "A synthesis algorithm for three-revolute manipulators by using an algebraic formulation of workspace boundary". ASME J. Mech. Des. 1995; 117(2(A)): 298-302.

[11] S. K. Agrawal. "Workspace boundaries of in-parallel manipulator systems". IEEE Transactions on Robotics and Automation, 7(2):94–99, 1991.

[12] F. Pernkopf and M. Husty, "Reachable Workspace and Manufacturing Errors of Stewart-Gough Manipulators", Proc. of MUSME 2005, the Int. Sym. on Multibody Systems and Mechatronics Brazil, 2005, p. 293-304.

[13] S. Stan, Diplomarbeit, Analyse und Optimierung der strukturellen Abmessungen von Werkzeugmaschinen mit Parallelstruktur, IWF-TU Braunschweig, 2003, Germany.

[14] C. Ferraresi, G. Montacchini, and M. Sorli. "Workspace and dexterity evaluation of 6 d.o.f. spatial mechanisms". In Proceedings of the ninth World Congress on the theory of Machines and Mechanism, pages 57–61, Milan, August 1995.

[15] M. Ceccarelli, G. Carbone, E. Ottaviano, "An Optimization Problem Approach For Designing Both Serial And Parallel Manipulators", Proc. of MUSME 2005, the Int. Sym. on Multibody Systems and Mechatronics Uberlandia, Brazil, 6-9 March 2005.