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Optimization of a 2 DOF Micro Parallel Robot Using Genetic Algorithms

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1. Introduction

Over the last couple of decades parallel robots have been increasingly studied and developed from both a theoretical viewpoint as well as for practical applications (Merlet, 1995). Advances in computer technology and development of sophisticated control techniques have allowed for the more recent practical implementation of parallel manipulators. Some of the advantages offered by parallel manipulators, when properly designed, include an excellent load-to-weight ratio, high stiffness and positioning accuracy and good dynamic behavior (Merlet 1995, Stan 2003). The ever-increasing number of publications dedicated to parallel robots illustrated very well this trend.

However, there are also some disadvantages associated with parallel manipulators, which have inhibited their application in some cases. Most serious of these is that the particular architecture of parallel manipulators leads to smaller manipulator workspaces than their serial counterparts.

One of the main influential factors on the performance of the micro parallel robot is its structural configuration. The kinematic relations, statics, dynamics and structure stiffness are all dependent upon it. After its choice, the next step on the manipulator design should be to establish its dimensions. Usually this dimensioning task involves the choice of a set of parameters that define the mechanical structure of the parallel robots. The parameter values should be chosen in a way to optimize some performance criterion, dependent upon the foreseen application. Micro parallel robots can also be difficult to design (Stan, 2003), since the relationships between design parameters and the workspace, and behavior of the manipulator throughout the workspace, are not intuitive by any means. This is one of the reasons why Merlet (1995) argues that customization of parallel manipulators for each application is absolutely necessary in order to ensure that all performance requirements can be met by the manipulator. As a result, development of design methodologies for such manipulators is an important issue in order to ensure performance to their full potential. In particular, the development and refinement of numerical methods for workspace determination of various parallel manipulators is of utmost importance.

There is a strong and complex link between the type of robot's geometrical parameters and its performance. It's very difficult to choose the geometrical parameters intuitively in such a way as to optimize the performance. Several papers have dealt with parallel robots to optimize performances (Stan, 2006). For example, various methods to determine workspace

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of a parallel robot have been proposed using geometric or numerical approaches. Early investigations of robot workspace were reported by Gosselin (1990), Merlet (1994) and Cecarelli (2004). Stan (2003) 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. A method was proposed to determine the workspace by using optimization (Stan, 2006).

In the next sections, the planar 2-dof micro parallel robot of interest, and the kinematics for this manipulator, is presented. The 2-dof micro parallel robot considered in this study is shown in Fig. 3, where its joints (A and C) connected to the ground are active and the others are passive joints. The input motions of the active joints can be independent from each other or be provided via a set of gears maintaining a specified phase angle between the two active joints.

The objective of this chapter is to propose an optimization method for a planar micro parallel robot that uses performance evaluation criteria related to the workspace of micro parallel robot. 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 (Stan, 2006).

2. Genetic Algorithms for Optimization of Micro Parallel Robots

2.1 Optimization based on Genetic Algorithms

Optimization is the process of making something better. An engineer or scientist conjures up a new idea and optimization improves on that idea. Optimization consists in trying variations on an initial concept and using the information gained to improve on the idea. Optimization is the process of adjusting the inputs to or characteristics of a device, mathematical process, or experiment to find the minimum or maximum output or result (Fig. 1). The input consists of variables, the process or function is known as the cost function, objective function, or fitness function, and the output is the cost or fitness. If the process is an experiment, then the variables are physical inputs to the experiment.

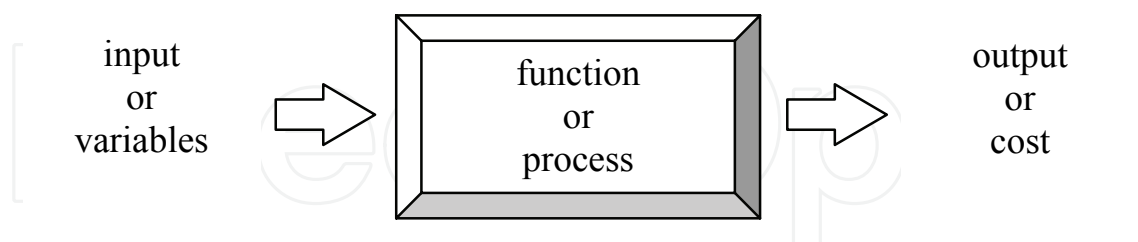


Figure 1. Diagram of a function or process that is to be optimized. Optimization varies the input to achieve a desired output

The genetic algorithm (GA) has been growing in popularity over the last few years as more and more researchers discover the benefits of its adaptive search. Genetic algorithms (GAs) were invented by John Holland in the 1960s and were developed by Holland and his students and colleagues at the University of Michigan in the 1960s and the 1970s. In contrast with evolution strategies and evolutionary programming, Holland's original goal was not to design algorithms to solve specific problems, but rather to formally study the phenomenon

of adaptation as it occurs in nature and to develop ways in which the mechanisms of natural adaptation might be imported into computer systems.

Holland's 1975 book *Adaptation in Natural and Artificial Systems* presented the genetic algorithm as an abstraction of biological evolution and gave a theoretical framework for adaptation under the GA. Holland's GA is a method for moving from one population of "chromosomes" (e.g., strings of ones and zeros, or "bits") to a new population by using a kind of "natural selection" together with the genetics-inspired operators of crossover, mutation, and inversion. Each chromosome consists of "genes" (e.g., bits), each gene being an instance of a particular "allele" (e.g., 0 or 1).

The selection operator chooses those chromosomes in the population that will be allowed to reproduce, and on average the fitter chromosomes produce more offspring than the less fit ones. Crossover exchanges subparts of two chromosomes, roughly mimicking biological recombination between two single-chromosome ("haploid") organisms; mutation randomly changes the allele values of some locations in the chromosome; and inversion reverses the order of a contiguous section of the chromosome, thus rearranging the order in which genes are arrayed. (Here, as in most of the GA literature, "crossover" and "recombination" will mean the same thing.)

In a broader usage of the term, a genetic algorithm is any population-based model that uses selection and recombination operators to generate new sample points in a search space. Many genetic algorithm models have been introduced by researchers largely working from an experimental perspective. Many of these researchers are application oriented and are typically interested in genetic algorithms as optimization tools. A constrained single-objective optimization problem can be converted to an unconstrained single-objective form by a penalty method (see, for example, Papalambros and Wilde, 1988).

Fig. 2 shows graphically how the most basic Genetic Algorithms operations are performed. The top block of binary numbers in Fig. 2 represents a population. Each row is an individual that represents one solution to the design problem. One individual is made up of all of the design variables concatenated. The GA user can decide how many binary digits are needed to represent each design variable.

In Fig. 2, there are 3 design variables of length 6, 7, and 4 binary digits. Initially, the population is generated randomly, and then the solutions are ranked from best to worst and a specified number of the lowest ranked individuals are replaced with combinations of the highest ranked individuals. The process of determining which of the highest ranked individuals are to be used is called selection. There are several differing methods of selection that can be used. Once selected, two individuals go through a process called crossover.

The crossover operation is also shown in Fig. 2, wherein two individuals (or parents) exchange a segment of the binary digits creating two new individuals (or offspring). Another basic Genetic A operation is mutation. Mutation can occur on the two individuals selected for crossover or on a single individual. The mutation operation randomly mutates or changes the bits within the individual based on the mutation probability set by the user.

Finding optimal values for the parameters used in the GA operations can be problematic. Parameter values that result in a relatively fast convergence for one problem may be slow for another. However, some general guidelines on the population size can be made on the basis of the binary string length of an individual.

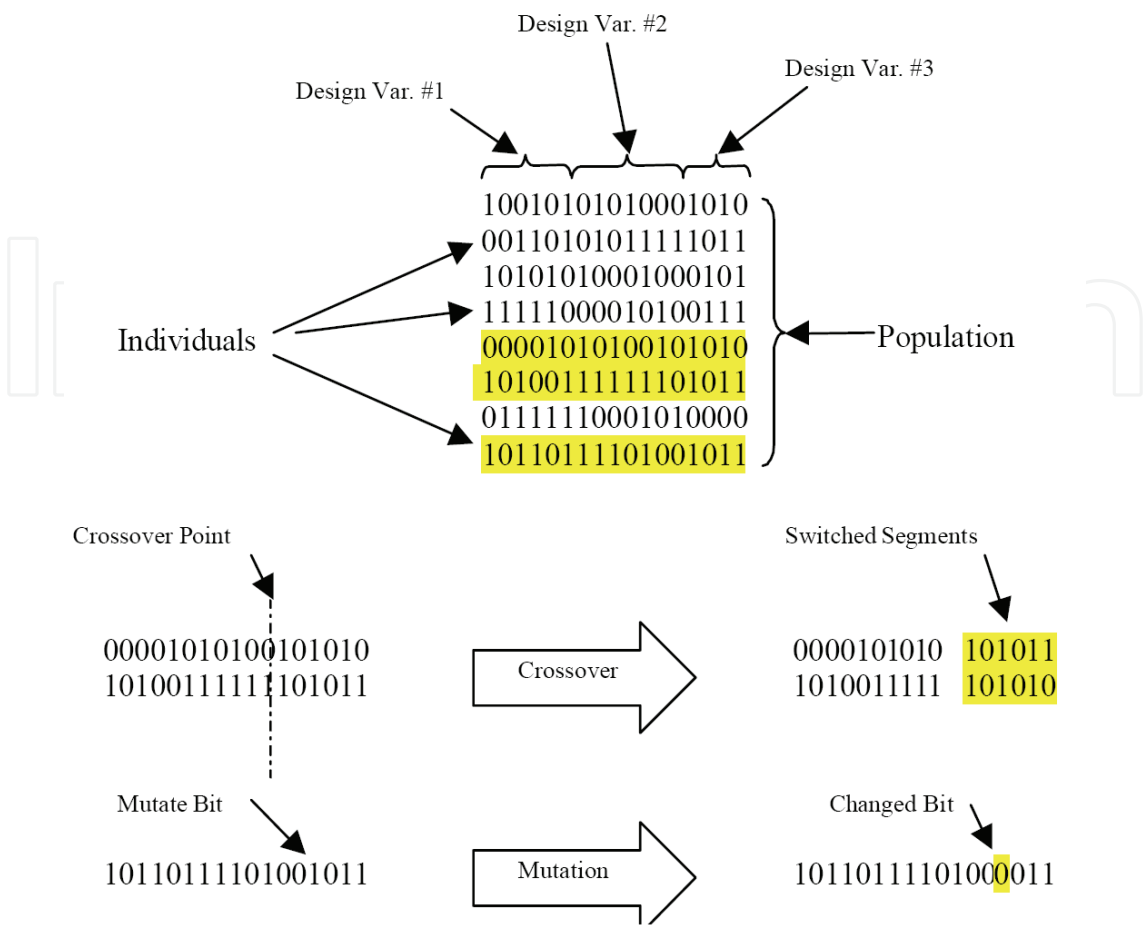


Figure 2. Graphical Description of Genetic Algorithms

Some of the advantages of a GA include that it:

- optimizes with continuous or discrete variables,
- doesn't require derivative information,
- simultaneously searches from a wide sampling of the cost surface,
- deals with a large number of variables,
- is well suited for parallel computers,
- optimizes variables with extremely complex cost surfaces (they can jump out of a local minimum),
- provides a list of optimum variables, not just a single solution,
- may encode the variables so that the optimization is done with the encoded variables,
- works with numerically generated data, experimental data, or analytical functions.

These advantages are intriguing and produce stunning results when traditional optimization approaches fail miserably.

2.2 Pareto-optimality

Multiobjective problems are special in the sense that they do not have a unique solution. Usually there is no single solution for which all objectives are optimal. The solution to a multiobjective problem therefore comprises a *set* of solutions for which holds that there are no other solutions that are superior considering *all* objectives. These solutions are called

Pareto-optimal. Hence, optimizing a multiobjective problem is comprised of finding Pareto optimal solutions.

The notion of Pareto-optimality is defined in terms of *dominance*. Let's assume that a multiobjective problem has k objectives. Assuming that this is a minimization problem, then a solution $x = (x_1, x_2, \dots, x_k)$ is said to dominate another solution $y = (y_1, y_2, \dots, y_k)$ if $\forall i \ x_i \leq y_i$ and $\exists i \ x_i < y_i$. Solution x is a member of the Pareto-set, or said to be *non-dominated*, if there is no other solution y such that y dominates x . The multiobjective problem can now be defined as finding solutions which are non-dominated.

Over the years, several evolutionary approaches to multiobjective problems have been introduced. The most commonly used approach is to combine the objective function into a single objective function using weighting coefficients and penalty functions. This problem-transformation enables the use of a simple single-objective genetic algorithm to find a single solution, which may be feasible, so requiring no further searches. Weights and penalty functions are generally hard to set accurately though, whereas both are very problem dependent (Richardson et al., 1989). As a result, the solution a GA comes up with may not fulfill all the designer's needs. The solution may not even be non-dominated. Setting the weights correctly requires a certain amount of search space knowledge, which is often not available in advance. This way of dealing with multiobjective optimization is therefore not always applicable or efficient.

Another, and perhaps more effective approach, is to use genetic algorithms to locate Pareto-optimal solutions. These solutions are, by definition, located on a boundary, known as the Pareto-front. We would like the solutions to cover the Pareto-front as well as possible, as to obtain a good representation of this front. This approach requires an extensive exploration of the search space and it is this requirement that makes evolutionary algorithms extremely applicable in this case. Their massive parallel exploration of search spaces is an invaluable advantage over other more conventional techniques in locating Pareto-optimal solutions. This Pareto-based approach has additional benefits as well. This approach offers multiple solutions from which a decision maker can select the solution that is best suited according to additional criteria, without requiring additional searches. Pareto based optimization is hence a more transparent and efficient way of dealing with multiobjective problem.

A Pareto solution is proper if the tradeoff rate between the objectives in the neighborhood of that solution is bounded. In other words, in the neighborhood of a proper Pareto point, a finite increase in one objective is possible only at the expense of some reasonable decrease in one other objective. A proper Pareto solution is a good candidate design solution (Stan, 2003).

3. Two DOF RRRRR Micro Parallel Robot

3.1 Geometrical description of the micro parallel robot

The micro parallel robot considered in this paper is the 2-dof planar parallel mechanism shown in Fig. 3. The micro parallel robot consists of a five-bar mechanism connected to a base by two rotary actuators, which control the two output degrees of freedom of the end-effector. The actuators are joined to the base and platform by means of revolute joints identified by the letters A-D. It will be assumed that $AO=OC=AC/2$. The coordinates of point P, the end-effector point, are (x_P, y_P) . In more general terms, the actuator joint angles are the input variables, i.e. $\mathbf{v}=[q_1, q_2]^T \in \mathbb{R}^2$. The global coordinates of the working point P

form the output coordinates, i.e. $\mathbf{u}=[x_P, y_P]^T \in \mathbb{R}^2$. The 2-dof micro parallel robot may be used only for positioning P in the x - y plane. It is evident that this manipulator thus has 2-dof. Thus, the generalized coordinates for this kind of micro parallel robot are therefore given by:

$$\mathbf{q}=[\mathbf{u}^T, \mathbf{v}^T]^T=[x_P, y_P, q_1, q_2]^T \in \mathbb{R}^4 \tag{1}$$

In general, factors imposed by the physical construction of the planar parallel manipulator, which limit the workspace, may be related to the input variables or a combination of input, output and intermediate variables. An example of former type for the planar parallel manipulator are joint angles limits, and of the latter, limits on the angular displacement of the revolute joints connecting the legs to the ground and to the platform. These limiting factors are described by means of inequality constraints and may, respectively, take the general forms:

$$\mathbf{v}^{\min} \leq \mathbf{v} \leq \mathbf{v}^{\max} \tag{2}$$

$$\mathbf{g}^{\min} \leq \mathbf{g}(\mathbf{u}, \mathbf{v}) \leq \mathbf{g}^{\max} \tag{3}$$

The above general definitions are necessary in order to facilitate the mathematical description of kinematics and workspaces of the 2-dof planar micro parallel robot. In this study mixed constraints, represented by (3), are not taken into consideration.

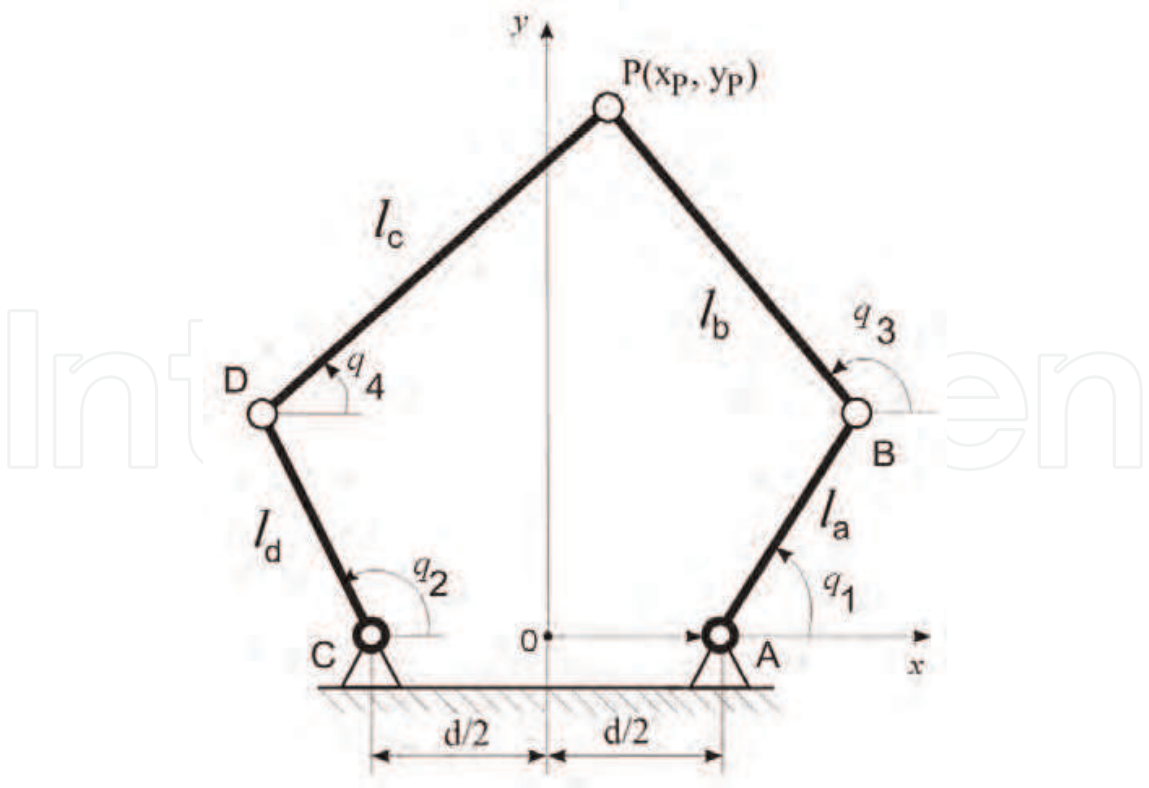


Figure 3. Micro parallel robot with 2 degrees of freedom

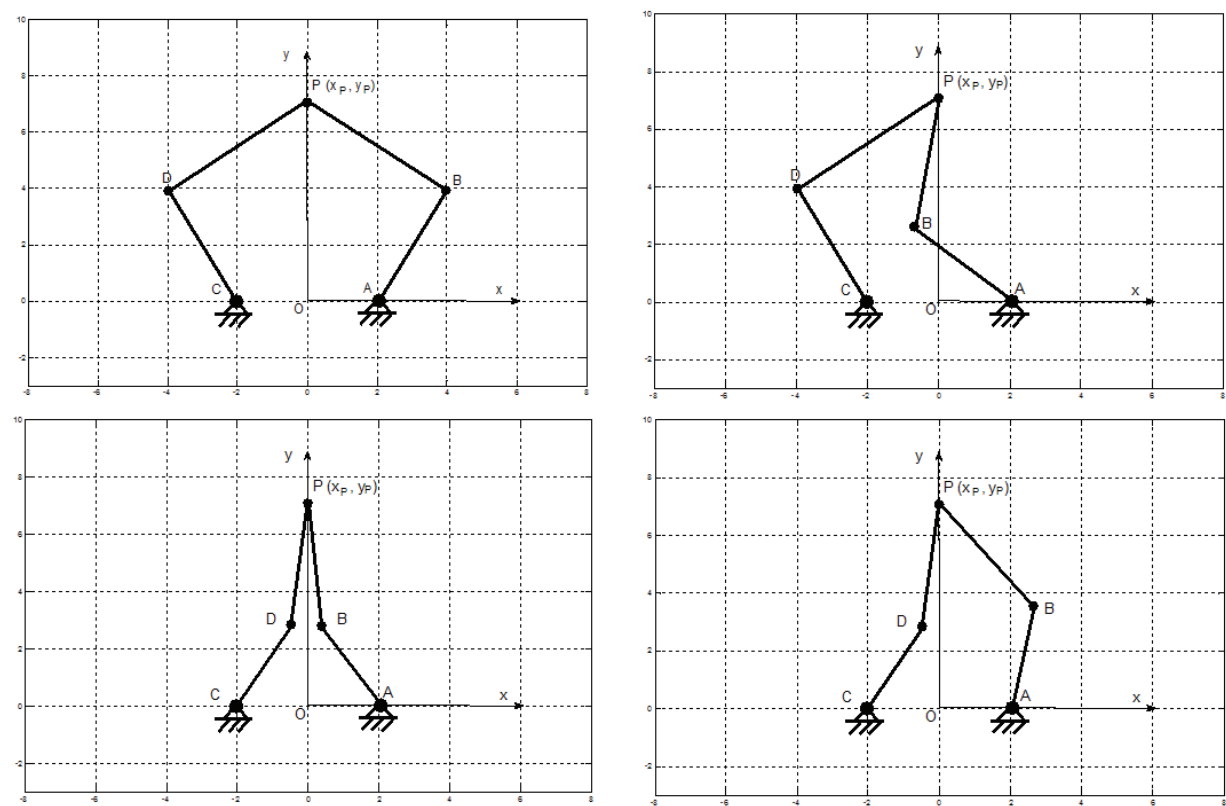


Figure 4. The 4 types of functioning of micro parallel robot with 2 degrees of freedom

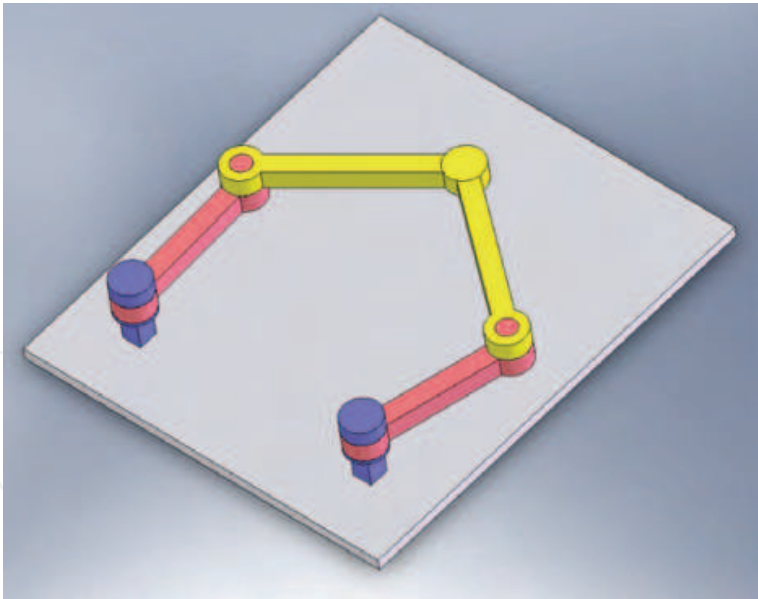


Figure 5. CAD model of the micro parallel robot of type RRRRR

3.2 The kinematics of the RRRRR micro parallel robot

Kinematic analysis of five-bar micro parallel robot is needed before carrying out derivations for the mathematical model. It is considered the five-bar micro parallel robot with revolute joints as in Fig. 1. It is known the length of the links as well as the fixed joints coordinates. The five-bar mechanism is symmetric toward Oy -axis, thus $l_a = l_d = l$ respectively $l_b = l_c = L$.

Actuators are placed in A and C . Attaching to each link a vector, on the $OABPO$ respectively $OCDPO$, we can write successively the relations:

$$\overrightarrow{OP} = \overrightarrow{OA} + \overrightarrow{AB} + \overrightarrow{BP}; \overrightarrow{OP} = \overrightarrow{OC} + \overrightarrow{CD} + \overrightarrow{DP} \quad (4)$$

Based on the above relations, the coordinates of the point P have the following forms:

$$\begin{aligned} x_P &= \frac{d}{2} + l \cos q_1 + L \cos q_3 = -\frac{d}{2} + l \cos q_2 + L \cos q_4 \\ y_P &= l \sin q_1 + L \sin q_3 = l \sin q_2 + L \sin q_4 \end{aligned} \quad (5)$$

In this part, kinematics of a planar micro parallel robot articulated with revolute type joints has been formulated to solve direct kinematics problem, where the position, velocity and acceleration of the micro parallel robot end-effector are required for a given set of joint position, velocity and acceleration.

The Direct Kinematic Problem (DKP) of micro parallel robot is an important research direction of mechanics, which is also the most basic task of mechanic movement analysis and the base such as mechanism velocity, mechanism acceleration, force analysis, error analysis, workspace analysis, dynamical analysis and mechanical integration. For this kind of micro parallel robot solving DKP is easy. Coordinates of point P in the case when values of joint angles are known q_1 and q_2 are obtained from relations:

$$x_P = \frac{-D \pm \sqrt{D^2 - 4BC}}{2C}, \quad y_P = \frac{A - x_P(x_B - x_D)}{y_B - y_D} \quad (6)$$

where:

$$\begin{aligned} A &= -\frac{1}{2}(x_D^2 + y_D^2 - x_B^2 - y_B^2 - L_{DP}^2 + L_{BP}^2) \\ B &= (y_B - y_D)^2(x_D^2 + y_D^2 - L_{DP}^2) + A^2 - 2y_D(y_B - y_D)A \\ C &= (y_B - y_D)^2 + (x_B - x_D)^2 \\ D &= 2y_D(y_B - y_D)(x_B - x_D) - 2x_D(y_B - y_D)^2 - 2A(x_B - x_D) \\ x_D &= -\frac{d}{2} + l \cos q_2 \quad y_D = l \sin q_2 \\ x_B &= \frac{d}{2} + l \cos q_1 \quad y_B = l \sin q_1 \end{aligned} \quad (7)$$

The speed of the point P is obtained differentiating the relations (1). Thus results:

$$J_A \cdot \begin{bmatrix} V_x \\ V_y \end{bmatrix} = J_B \cdot \begin{bmatrix} \omega_1 \\ \omega_3 \end{bmatrix} \quad (8)$$

where

$$J_A = \begin{bmatrix} L \cos q_3 & L \sin q_3 \\ L \cos q_4 & L \sin q_4 \end{bmatrix} \quad (9)$$

$$J_B = \begin{bmatrix} l \cdot L \sin(q_1 - q_3) & 0 \\ 0 & l \cdot L \sin(q_2 - q_4) \end{bmatrix} \quad (10)$$

or

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = J \cdot \begin{bmatrix} \omega_1 \\ \omega_3 \end{bmatrix} \quad (11)$$

where

$$J = J_B J_A^{-1} = \frac{L}{\sin(q_4 - q_3)} \begin{pmatrix} \sin q_4 \sin(q_1 - q_3) & -\sin q_3 \sin(q_2 - q_4) \\ -\cos q_4 \sin(q_1 - q_3) & \cos q_3 \sin(q_2 - q_4) \end{pmatrix} \quad (12)$$

and J represents the Jacobian matrix.

Acceleration of the point P is obtained by differentiating of relation (8), as it yields:

$$\begin{bmatrix} A_x \\ A_y \end{bmatrix} = J \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_3 \end{bmatrix} + \frac{d}{dt} J \cdot \begin{bmatrix} \omega_1 \\ \omega_3 \end{bmatrix} \quad (13)$$

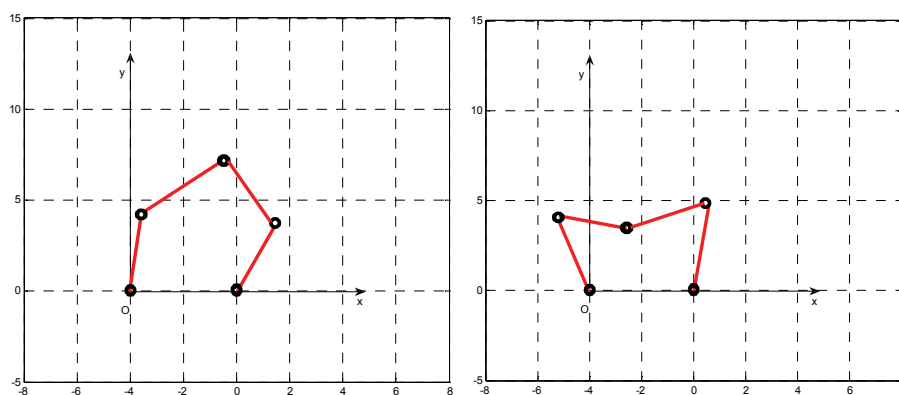


Figure 6. The two forward kinematic models: (a) the up-configuration and (b) the down-configuration

Based on the inverse kinematics analysis are determined the motion laws of the actuator links function of the kinematics parameters of point P .

The values of joint angles q_i , ($i = 1 \dots 4$) knowing the coordinates x_P , y_P of point P , may be computed with the following relations:

$$\begin{aligned}
 q_1 &= 2 \operatorname{arctg} \left(\frac{-B + \sigma_i \sqrt{B^2 - (C^2 - A^2)}}{C - A} \right) \\
 q_3 &= \operatorname{arctg} \left(\frac{\sqrt{M^2 + N^2 - P^2}}{P} \right) + \operatorname{arctg} \left(\frac{N^2}{M^2} \right) \\
 q_2 &= 2 \operatorname{arctg} \left(\frac{-B + \sigma_i \sqrt{B^2 - (f^2 - e^2)}}{f - e} \right) \\
 q_4 &= 2 \operatorname{arctg} \left(\frac{-b \pm \sqrt{b^2 - (F^2 + E^2)}}{F - E} \right), \quad \sigma_i = 1 \text{ or } -1
 \end{aligned} \tag{14}$$

where

$$\begin{aligned}
 A &= -2l \left(x_P - \frac{d}{2} \right) \\
 a &= -2L \left(x_P - \frac{d}{2} \right) \\
 C &= \left(x_P - \frac{d}{2} \right)^2 + y_P^2 + l^2 - L^2 \\
 M &= 2L\lambda \\
 N &= 2L\mu \\
 b &= -2y_P L \\
 c &= \left(x_P - \frac{d}{2} \right)^2 + y_P^2 - l^2 - L^2 \\
 e &= -2l \left(x_P + \frac{d}{2} \right) \\
 f &= \left(x_P + \frac{d}{2} \right)^2 + y_P^2 + l^2 - L^2 \\
 B &= -2y_P l
 \end{aligned} \tag{15}$$

$$F = \left(x_P + \frac{d}{2}\right)^2 + y_P^2 - l^2 + L^2$$
$$E = -2L\left(x_P + \frac{d}{2}\right)$$
$$P = -\lambda^2 - \mu^2$$
$$\lambda = l \cdot \cos q_1 - l \cdot \cos q_2 + d$$
$$\mu = l \cdot \sin q_1 - l \cdot \sin q_2$$

From Eq. (14), one can see that there are four solutions for the inverse kinematics problem of the 2-dof micro parallel robot. These four inverse kinematics models correspond to four types of working modes (see Fig. 7).

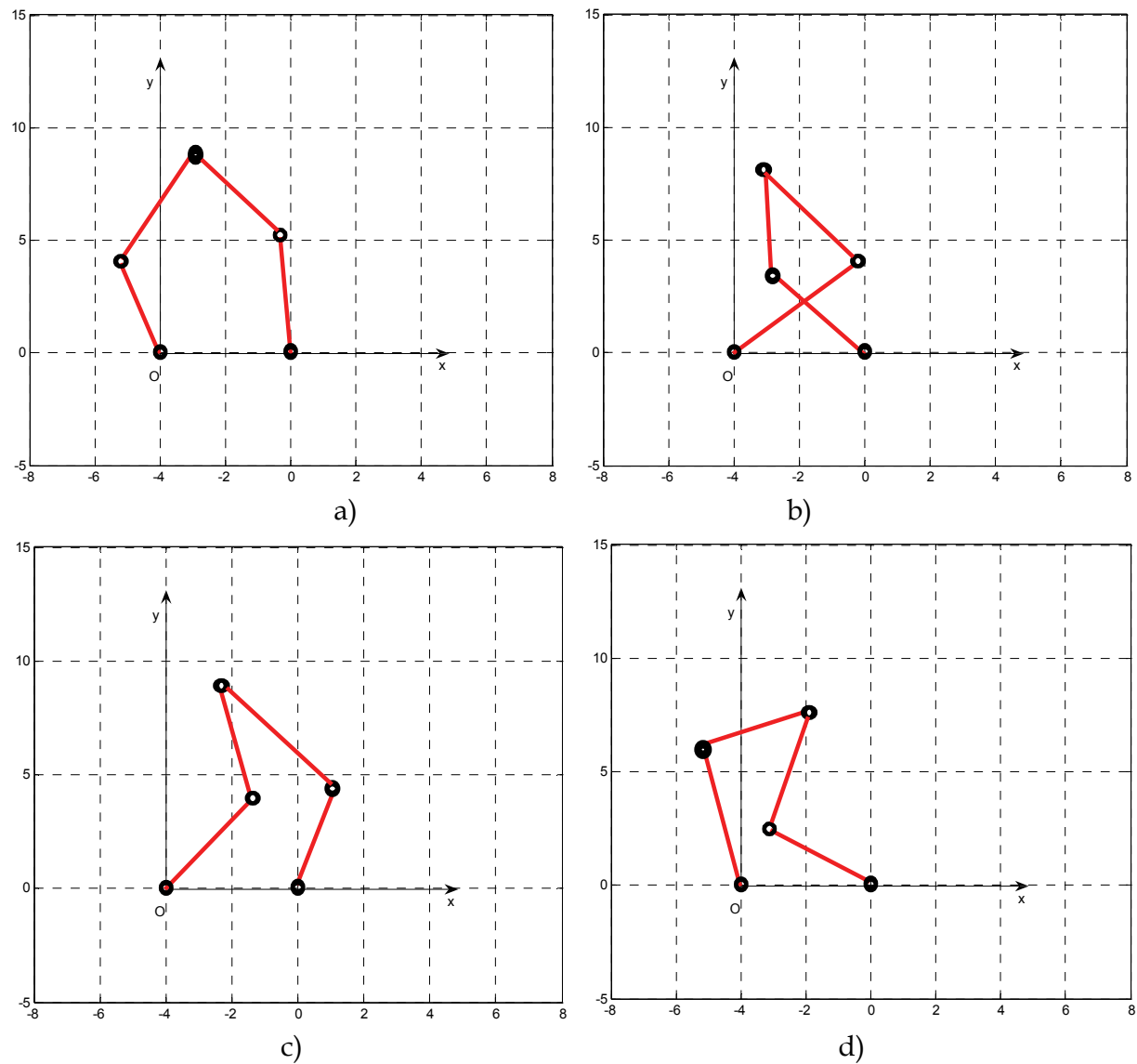


Figure 7. The four inverse kinematics models: (a)''+-'' model; (b)'' -+'' model; (b)'' --'' model; (d)'' ++'' model

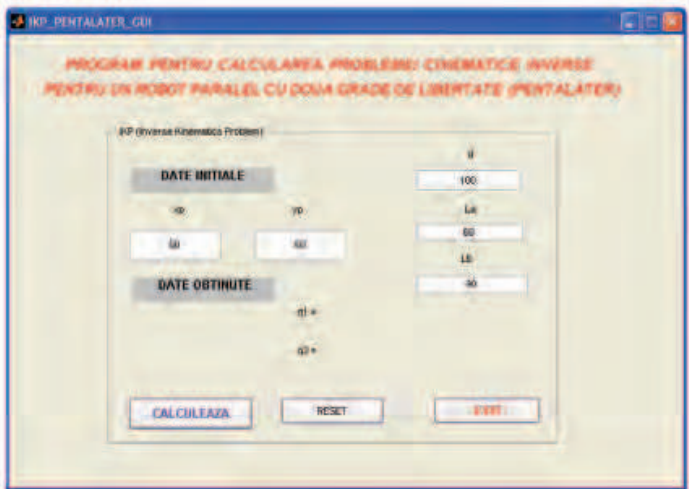


Figure 8. Graphical User Interface for solving the inverse kinematics problem of 2 DOF micro parallel robot

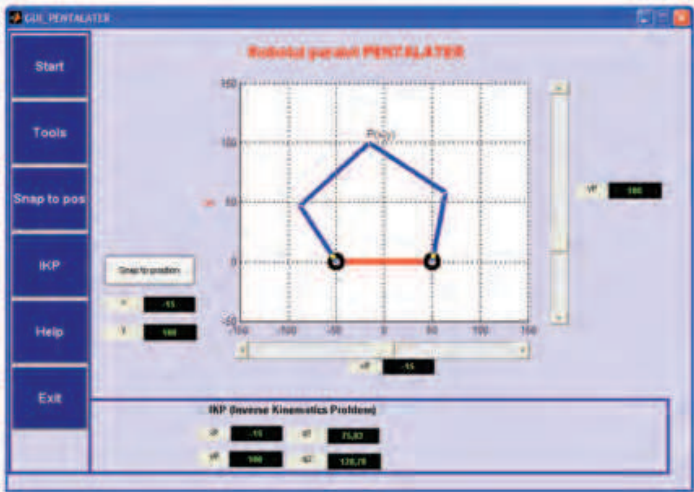


Figure 9. Robot configuration for micro parallel robot $x_P=-15$ mm $y_P=100$ mm

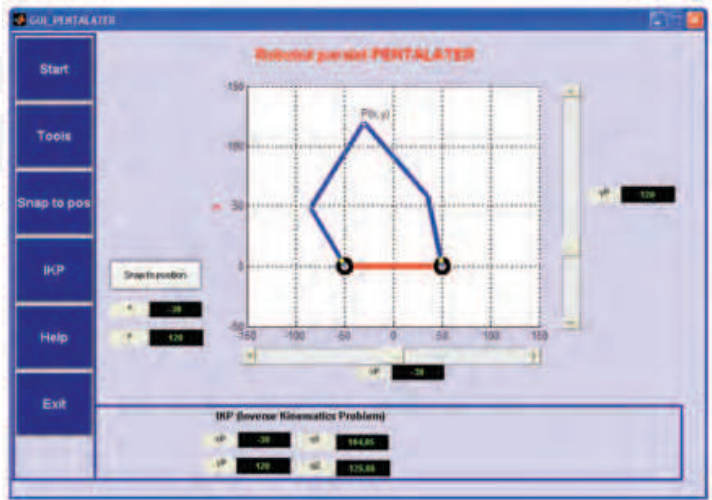


Figure 10. Robot configuration for micro parallel robot $x_P=-30$ mm $y_P=120$ mm

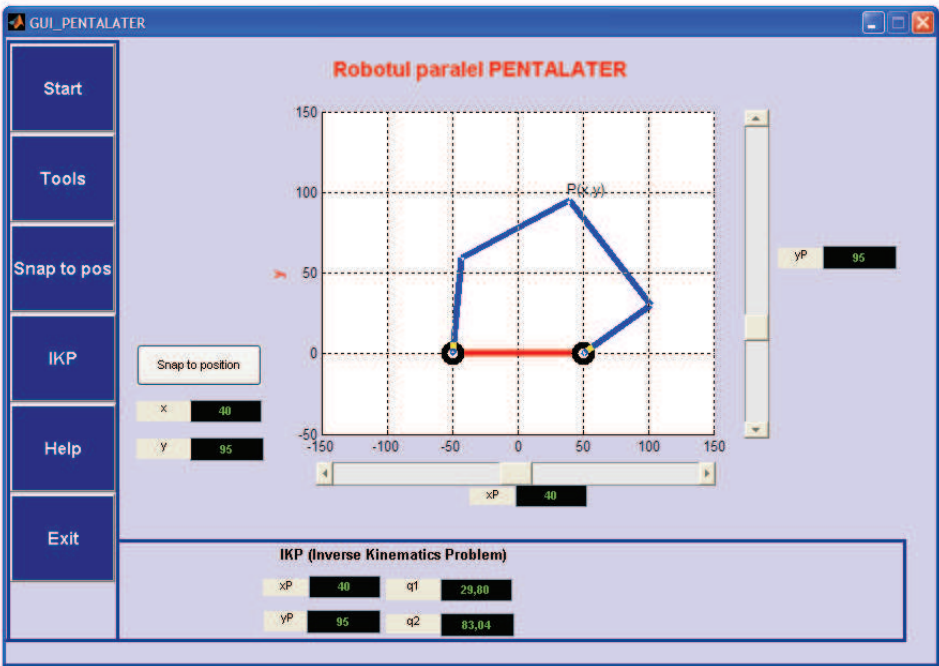


Figure 11. Robot configuration for micro parallel robot $x_P=40$ mm $y_P=95$ mm

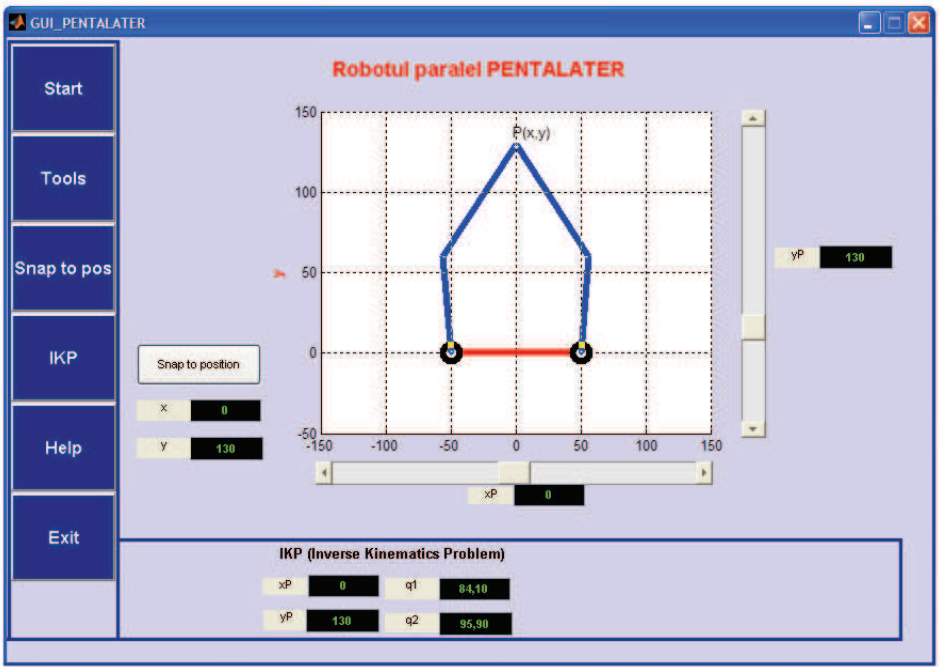


Figure 12. Robot configuration for micro parallel robot $x_P=0$ mm $y_P=130$ mm

3.3 Singularities analysis of the planar 2-dof micro parallel robot

In the followings, vector \mathbf{v} is used to denote the actuated joint coordinates of the manipulator, representing the vector of kinematic input. Moreover, vector \mathbf{u} denotes the Cartesian coordinates of the manipulator gripper, representing the kinematic output. The velocity equations of the micro parallel robot can be rewritten as:

$$A\dot{\mathbf{u}} + B\dot{\mathbf{v}} = \mathbf{0}$$

(16)

Where $\dot{\mathbf{v}} = [\dot{q}_1, \dot{q}_2]^T, \dot{\mathbf{u}} = [\dot{x}_p, \dot{y}_p]^T$ and where \mathbf{A} and \mathbf{B} are square matrices of dimension 2, called Jacobian matrices, with 2 the number of degrees of freedom of the micro parallel robot. Referring to Eq. (13), (Gosselin and Angeles, 1990), has defined three types of singularities which occur in parallel kinematics machines.

(I) The first type of singularity occurs when $\det(\mathbf{B})=0$. These configurations correspond to a set of points defining the outer and internal boundaries of the workspace of the micro parallel robot.

(II) The second type of singularity occurs when $\det(\mathbf{A})=0$. This kind of singularity corresponds to a set of points within the workspace of the micro parallel robot.

(III) The third kind of singularity when the positioning equations degenerate. This kind of singularity is also referred to as an architecture singularity (Stan, 2003). This occurs when the five points ABCDP are collinear.

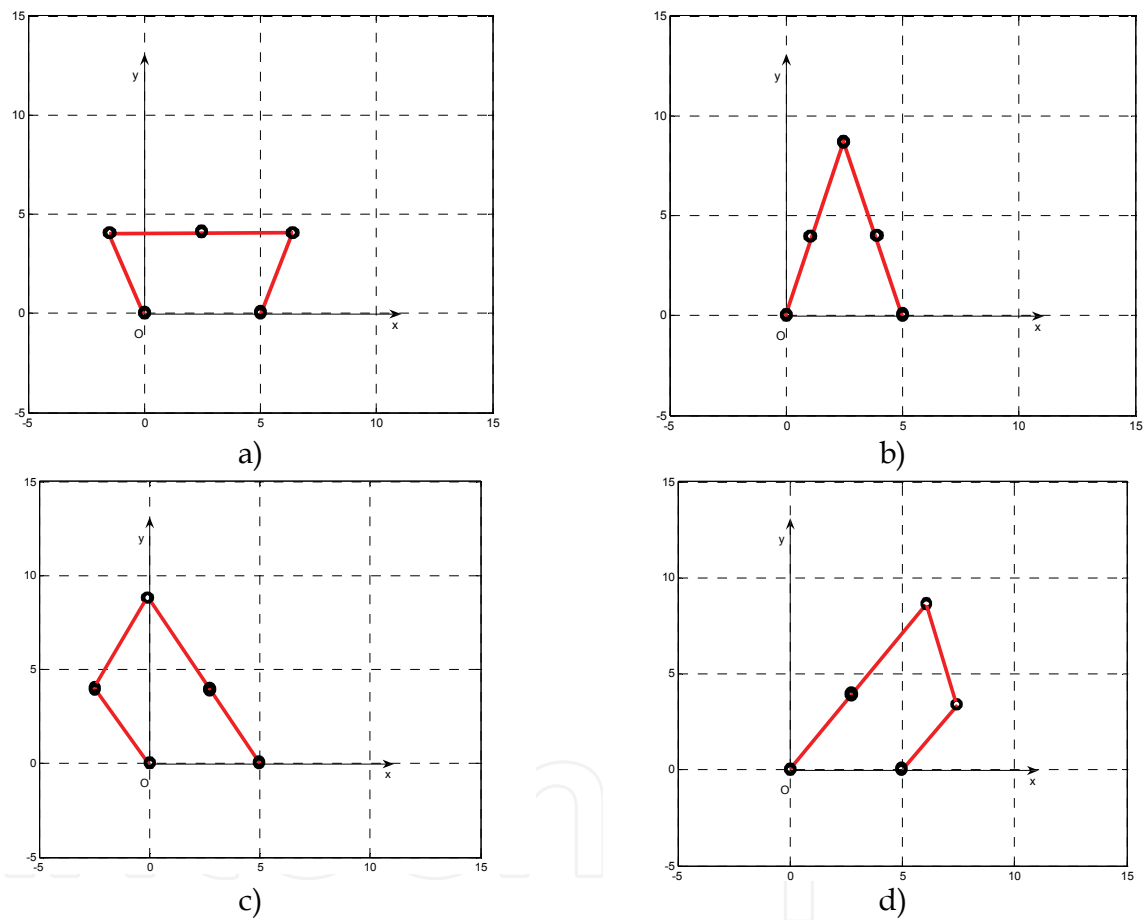


Figure 13. Some configurations of singularities: (a) the configuration when l_b and l_c are completely extended (b) both legs are completely extended; (c) the second leg is completely extended and (d) the first leg is completely extended

In this chapter, it will be used to analyze the second type of singularity of the 2-dof micro parallel robot introduced above in order to find the singular configuration with this type of micro parallel robot. For the first type of singularity, the singular configurations can be obtained by computing the boundary of the workspace of the micro parallel robot.

Furthermore, it is assumed that the third type of singularity is avoided by a proper choice of the kinematic parameters.

For this micro parallel robot, we can use the angular velocities of links l_c and l_b as the output vector. Matrix A is then written as:

$$A = \begin{bmatrix} l_c \cdot \cos(q_4) & -l_b \cdot \cos(q_3) \\ l_c \cdot \sin(q_4) & -l_b \cdot \sin(q_3) \end{bmatrix} \quad (17)$$

From Eq. (17), one then obtains:

$$\det(A) = l_c \cdot l_b \cdot \sin(q_4 - q_3). \quad (18)$$

From Eq. (18), it is clear that when $q_4 = q_3 + n\pi$, $n = 0, \pm 1, \pm 2, \dots$, then $\det(A) = 0$. In other words if the two links l_c and l_b are along the same line, the micro parallel robot is in a configuration which corresponds to be second type of singularity.

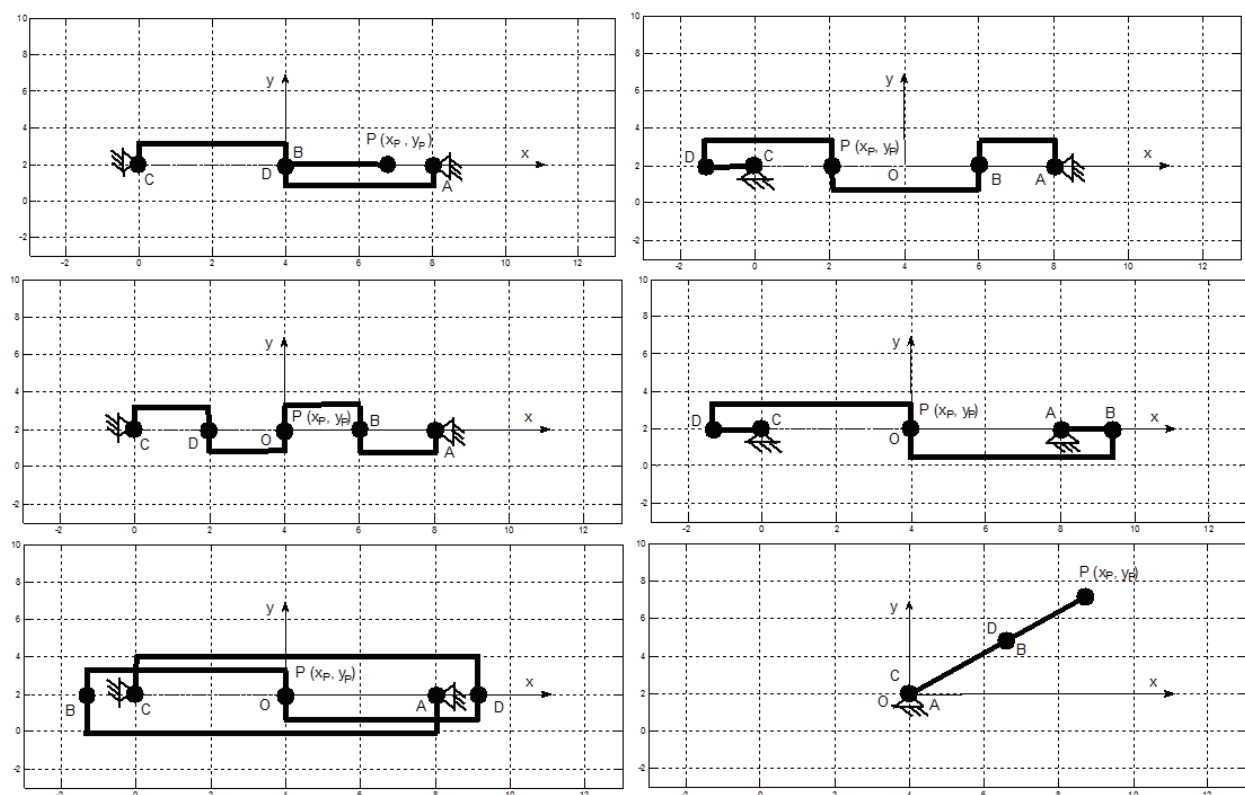


Figure 14. Examples of architectural singular configurations of the RRRRR micro parallel robot

3.4 Optimal design of the planar 2-dof micro parallel robot

The performance index chosen corresponds to the workspace of the micro parallel robot. Workspace is defined as the region that the output point P can reach if q_1 and q_2 changes from 2π without the consideration of interference between links and the singularities. There

were identified five types of workspace shapes for the 2-dof micro parallel robot as it can be seen in Figs. 15-20.

Each workspace is symmetric about the x and y axes. Workspace was determined using a program made in MATLAB™. Analysis, visualization of workspace is an important aspect of performance analysis. A numerical algorithm to generate reachable workspace of parallel manipulators is introduced.

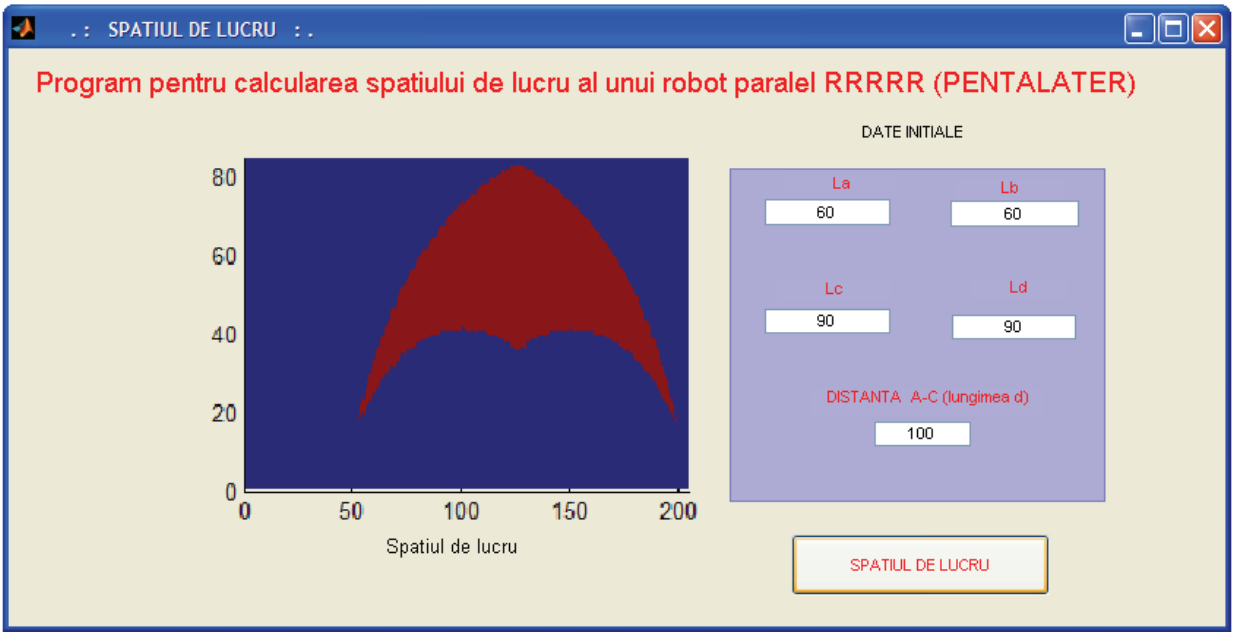


Figure 15. The GUI for calculus of workspace for the planar 2 DOF micro parallel robot

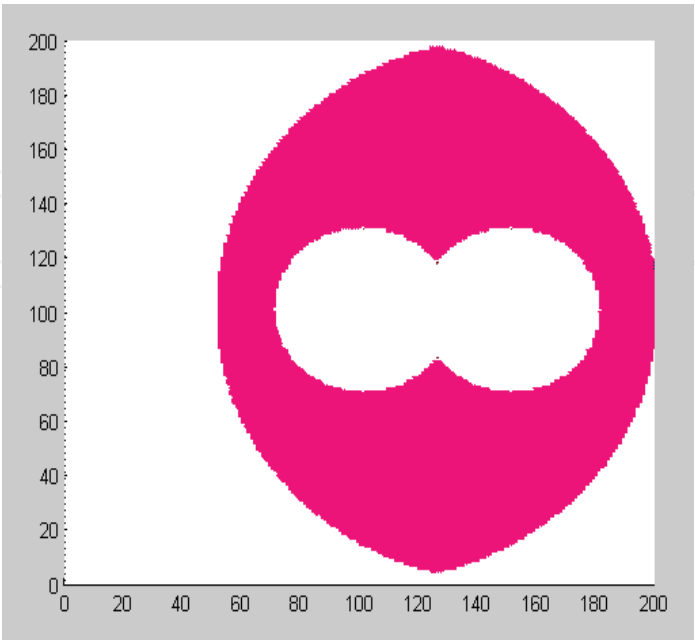


Figure 16. Workspace of the 2 DOF micro parallel robot

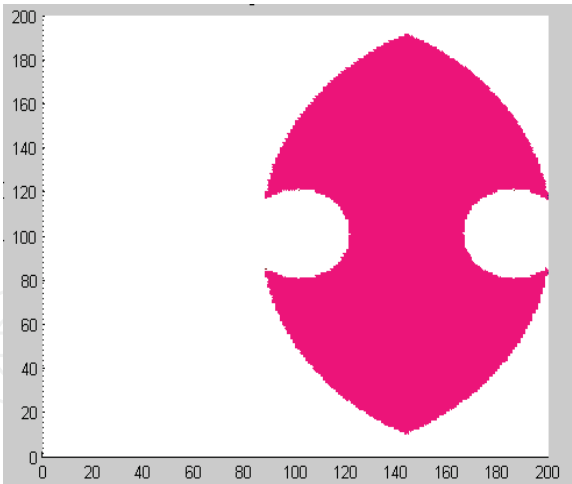


Figure 17. Workspace of the 2 DOF micro parallel robot

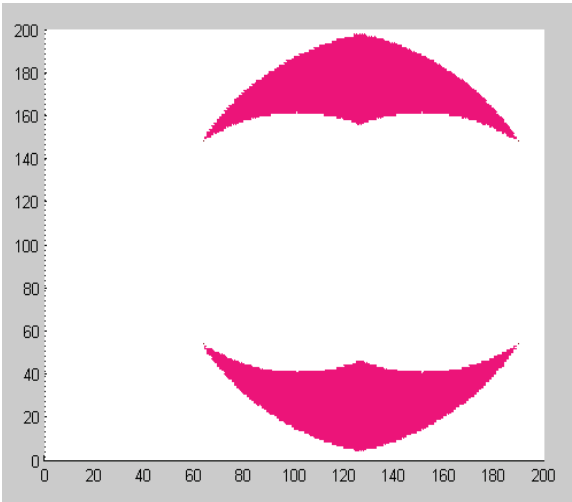


Figure 18. Workspace of the 2 DOF micro parallel robot

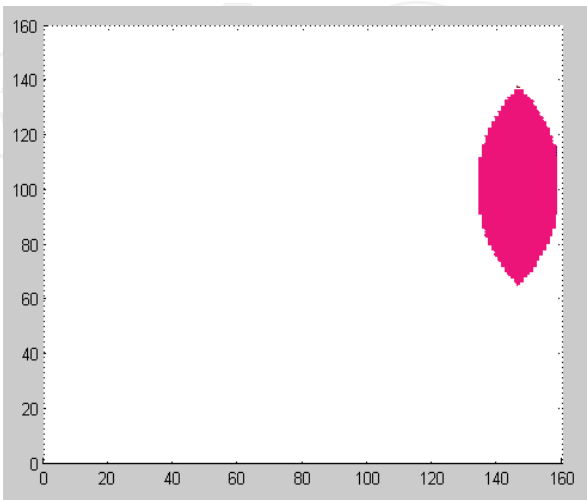


Figure 19. Workspace of the 2 DOF micro parallel robot

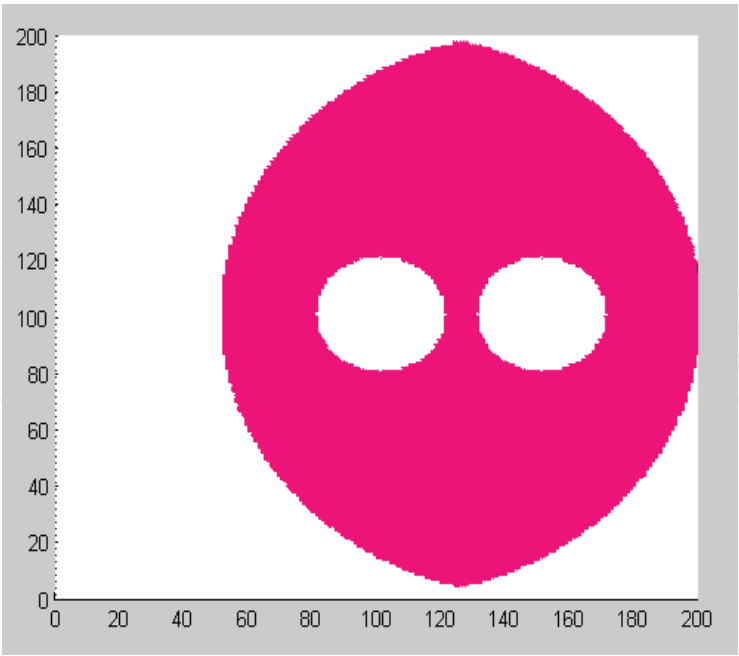


Figure 20. Workspace of the 2 DOF micro parallel robot

The above design of 2 DOF micro parallel robot employed mainly traditional optimization design methods. However, these traditional optimization methods have drawbacks in finding the global optimal solution, because it is so easy for these traditional methods to trap in local minimum points (Stan, 2003).

GA refers to global optimization technique based on natural selection and the genetic reproduction mechanism. GA is a directed random search technique that is widely applied in optimization problems. This is especially useful for complex optimization problems where the number of parameters is large and the analytical solutions are difficult to obtain. GA can help to find out the optimal solution globally over a domain.

The design of the micro parallel robot can be made based on any particular criterion. Here a genetic algorithm approach was used for workspace optimization of 2 DOF micro parallel robot.

For simplicity of the optimization calculus a symmetric design of the structure was chosen. In order to choose the robot dimensions d, l_a, l_b, l_c, l_d we need to define a performance index to be maximized. The chosen performance index is workspace W .

One objective function is defined and used in optimization. It is noted as W , and corresponds to the optimal workspace. We can formalize our design optimization problem as the following equation:

$$\text{Obj_function}=\max(W) \tag{19}$$

Optimization problem is formulated as follows: the objective is to evaluate optimal link lengths which maximize (16). 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:

$$l_d/d \tag{20}$$

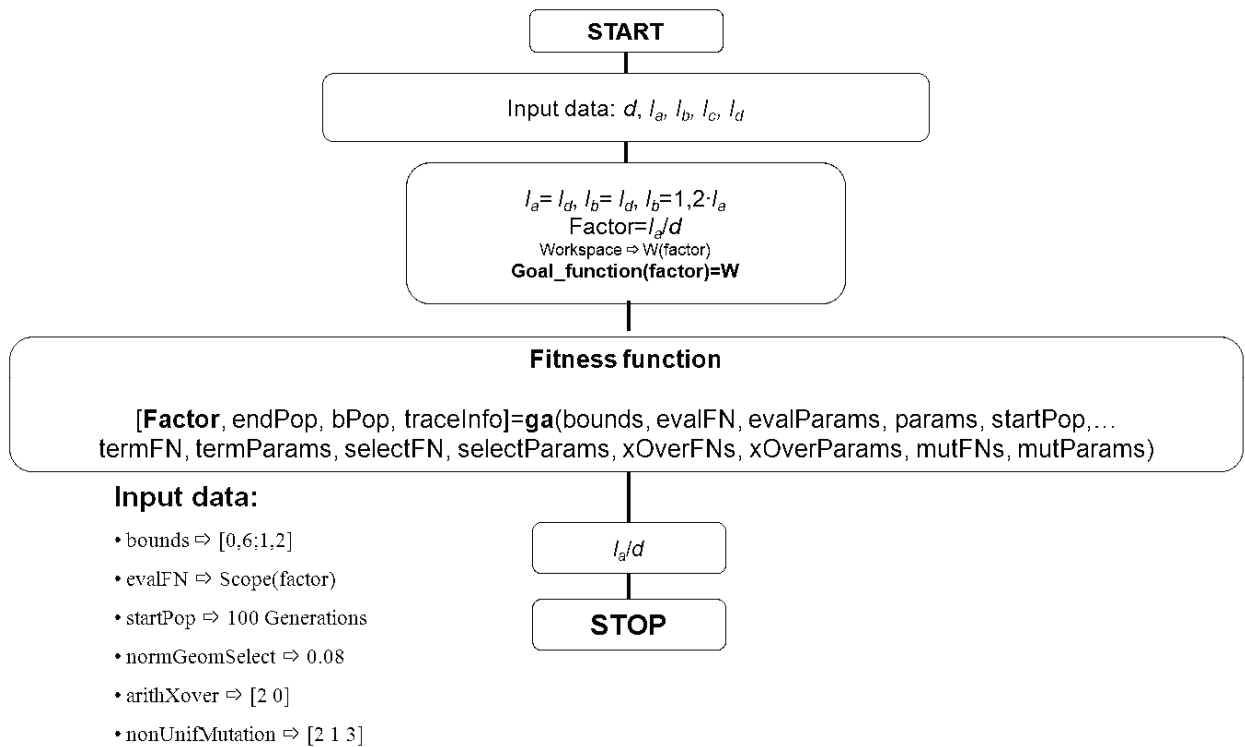


Figure 21. Flowchart of the optimization Algorithm with GAOT (Genetic Algorithm Optimization Toolbox)

Constraints to the design variables are:

$$0,6 < l_d/d < 1,2 \tag{21}$$

$$l_a = l_d, \quad l_b = l_c, \quad l_b = 1,2 l_a \tag{22}$$

For this example the lower limit of the constraint was chosen to fulfill the condition $l_d \geq d/2$. For simplicity of the optimization calculus the upper bound was chosen $l_d \leq 1,2d$. 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. We performed a kinematic optimization in such a way to maximize the workspace index W . It is noticed that optimization result for micro parallel robot when the maximum workspace of the 2 DOF planar micro parallel robot is obtained for $l_d / d = 1,2$. The used dimensions for the 2 DOF parallel micro robot were: $l_a = 72$ mm, $l_b = 87$ mm, $l_c = 87$ mm, $l_d = 72$ mm, $d = 60$ mm. Maximum workspace of the micro parallel robot was found to be $W = 9386$ mm². The results show that GA can determine the architectural parameters of the robot that provide an optimized workspace. Since the workspace of a micro parallel robot is far from being intuitive, the method developed should be very useful as a design tool.

1	Population	50
2	Generations	100
3	Crossover rate	0,08
4	Mutation rate	0,005

Table 1. GA Parameters

However, in practice, optimization of the micro parallel 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.

In the second case of optimization of the 2 DOF micro parallel robot there have been used 4 optimization criteria:

- 1. *transmission quality index* → $T=1$ the best value and the maximum one
- 2. *workspace* → a higher value is desirable
- 3. *stiffness index* → a higher value is desirable
- 4. *manipulability index* → a higher value is desirable

Beside workspace which is an important design criterion, transmission quality index is another important criterion.

The transmission quality index couples velocity and force transmission properties of a parallel robot, i.e. power features (Hesselbach et al., 2003). Its definition runs:

$$T = \frac{\|I\|^2}{\|J\| \cdot \|J^{-1}\|} \tag{23}$$

where I is the unity matrix.
 T is between $0 < T < 1$; $T=0$ characterizes a singular pose, the optimal value is $T=1$ which at the same time stands for isotropy (Hesselbach et al., 2003).

The manipulability condition number is a quality number in the sense of Yoshikawa, can be defined in terms of the ratio of a measure of performance in the task space and a measure of effort in the joint space.

$$M = \sqrt{\det(J \cdot J^T)} \tag{24}$$

If J is quadratic Eq. (4) reduces to $M=\det(J)$. The goal is to have a value of M as large as possible.

The stiffness condition number runs using the matrix K :

$$S = \|K^{-1}\| \cdot \|K\| = \|J \cdot J^T\| \cdot \|(J \cdot J^T)^{-1}\| \tag{25}$$

If the guiding chains of the machine between frame and working platform have different stiffness, the matrix K must be replaced by the matrix:

$$K_C = (J^T)^{-1} \cdot C \cdot J^{-1} \tag{26}$$

where the diagonal matrix C contains the stiffness of the single guiding chain. The reciprocal value of S is between $0 < 1/S \leq 1$; a singular pose is again characterized by $1/S = 0$, whereas $1/S = 1$ is the optimal (isotropic) index.

In the following figures, the performances evaluation throughout the workspace of the planar 2 DOF micro parallel robot is presented.

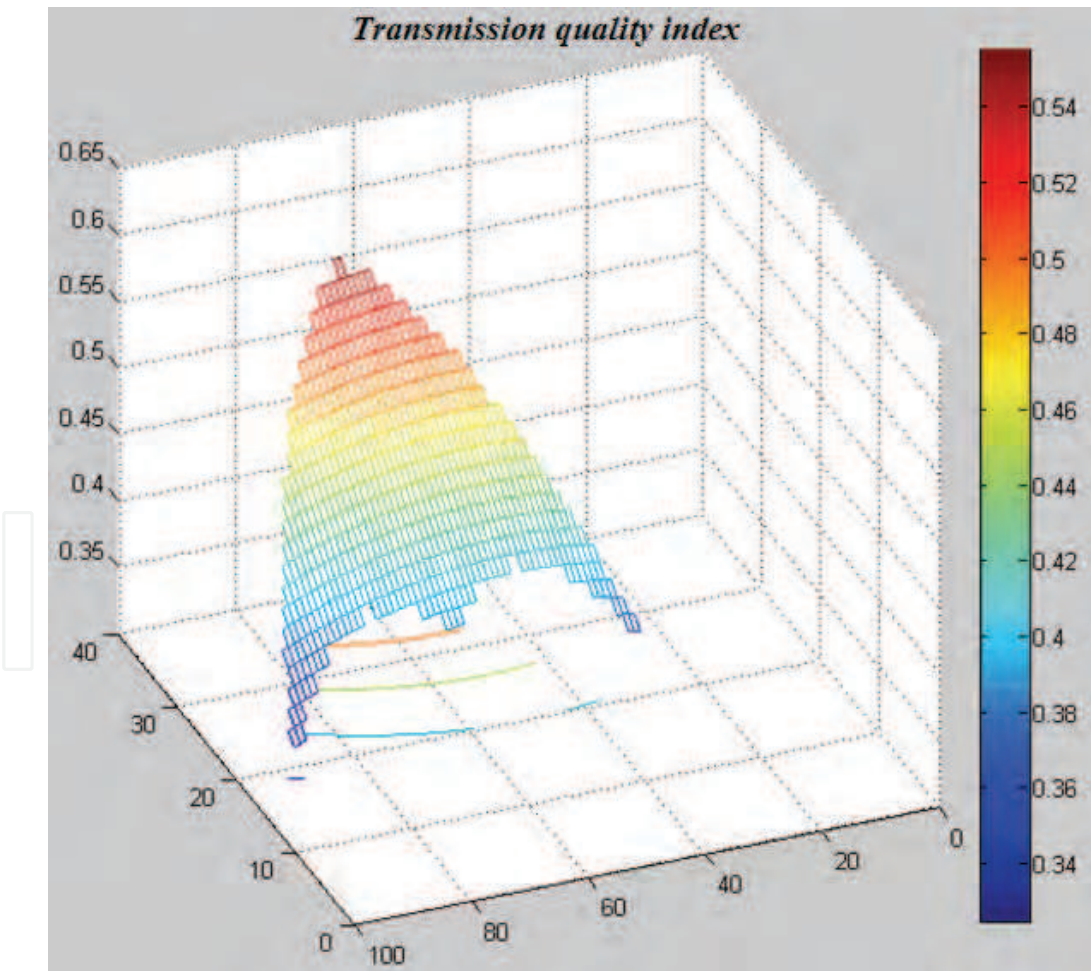


Figure 22. Transmission quality index for 2 DOF micro parallel robot

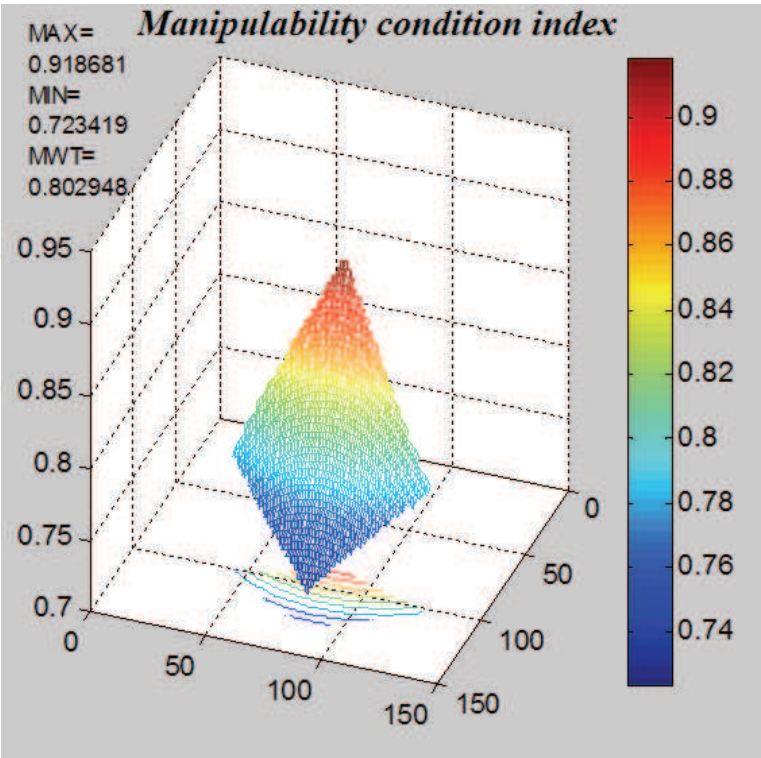


Figure 23. Manipulability index for 2 DOF micro parallel robot

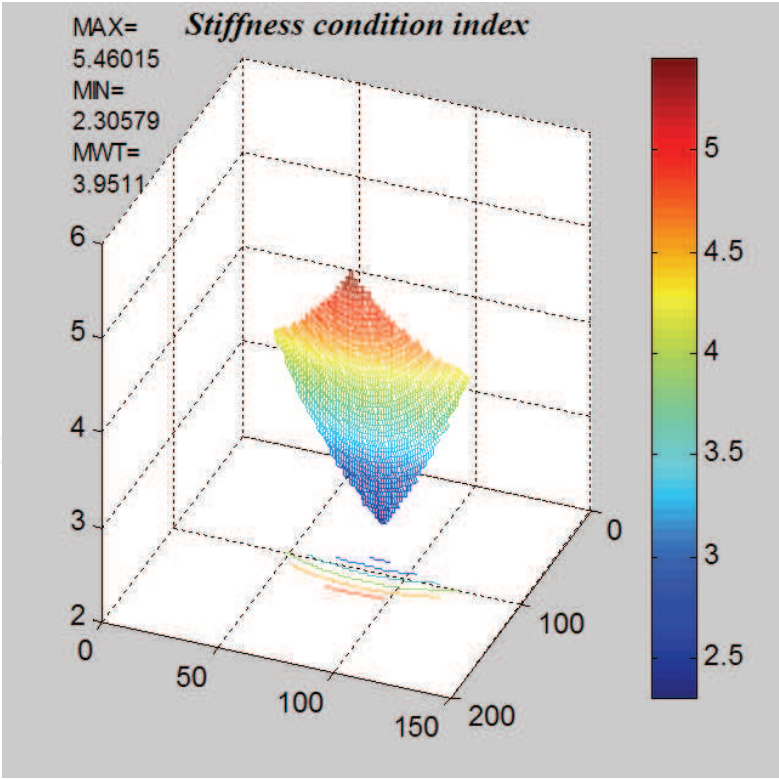


Figure 24. Stiffness index for 2 DOF micro parallel robot

Objective function:

$$\text{Obj_Fun} = f(T, A, S, M)$$

Optimization parameters:

$$l_d \text{ and } d$$

Constraints:

$$80 \leq l_d \leq 110 \text{ and } 90 \leq d \leq 120$$

Optimization problem is formulated as maximization of the objective function:

$$\max(\text{Obj_fun}(l_d, d)). \tag{27}$$

In Fig. 25 the Pareto front for optimization of a five-bar parallel micro robot for 4 optimization criteria, transmission quality index, workspace, manipulability and stiffness, is presented. For finding the Pareto front have been generated by a number of 500 generations. This approach focuses around the concept of Pareto optimality and the Pareto optimal set. Using these concepts of optimality of individuals evaluated under a multi objective problem, they each propose a fitness assignment to each individual in a current population during an evolutionary search based upon the concepts of dominance and non-dominance of Pareto optimality. More details regarding the developing the Pareto front can be found in (Stan, 2003).

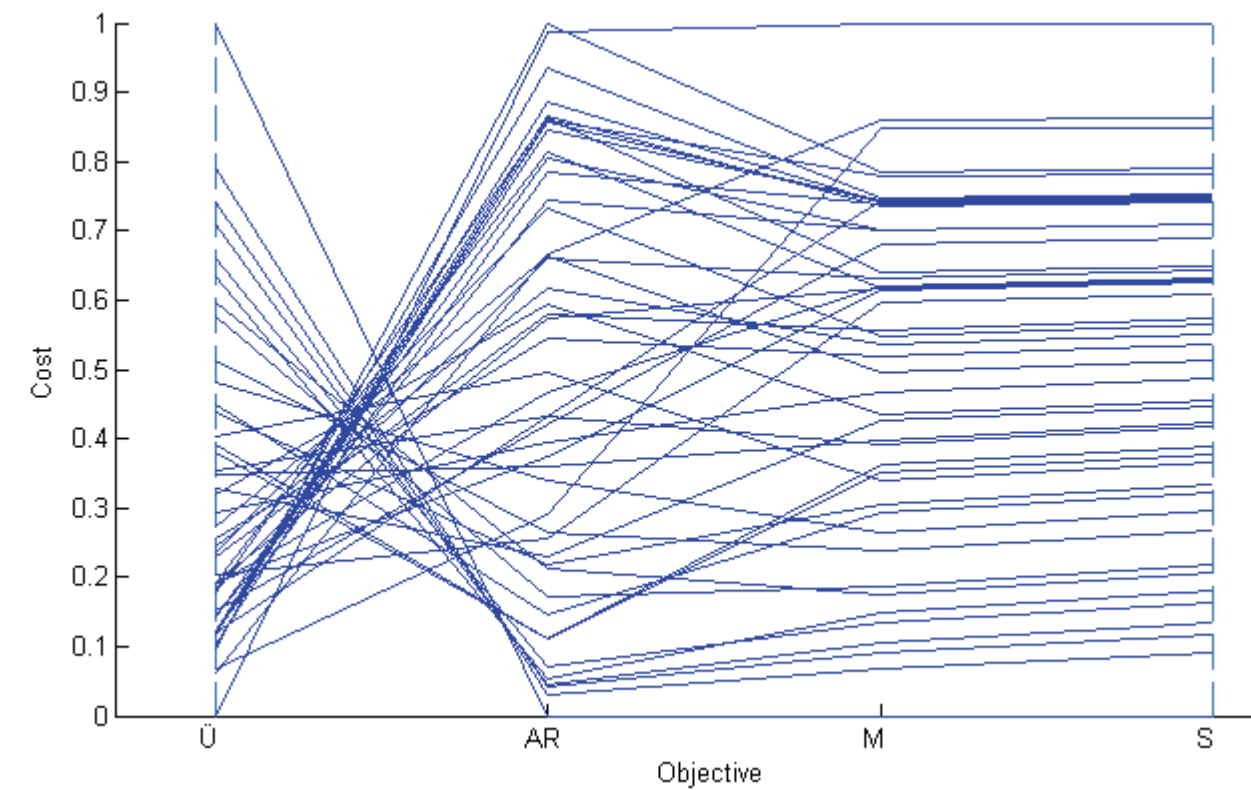


Figure 25. Pareto front for 4 optimization criteria: transmission quality index, workspace, manipulability and stiffness.

Since the finding of the solution for the multicriteria optimization doesn't end without choosing a compromise, there isn't need for an extreme precision for the values of the extreme positions. As Kirchner proved in (Kirchner and Neugebauer, 2000), optimization can be helped by a good starting population. The quality of the optimization depends essentially on the calculated number of generations.

In functioning of the genetic algorithms there have been used the following genetic algorithms parameters:

Size of population:	50
Generations:	10
Crossover rate:	0,07
Mutation rate:	0,01
Maximum number of generations:	500

Table 2. The GA Parameters

Based on the presented optimization methodology we can conclude that the optimum design and performance evaluation of the micro parallel robot is the key issue for an efficient use of micro 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, isotropy.

4. Conclusion

An optimization design of 2-dof micro parallel robot is performed with reference to kinematic objective function. Optimum dimensions can be obtained by using the optimization method. Finally, a numerical example is carried out, and the simulation result shows that the optimization method is feasible. The main purpose of the chapter is to present kinematic analysis and to investigate the optimal dynamic design of 2-dof micro parallel robot by deriving its mathematical model. By means of these equations, optimal design for 2-dof micro parallel robot is taken by using GA. Optimal design is an important subject in designing a 2-dof micro parallel robot. Here, intended to show the advantages of using the GA, we applied it to a multicriteria optimization problem of a 2 DOF micro parallel robot. 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. Pareto front was found and non-dominated solutions on this front can be chosen by the decision-maker.

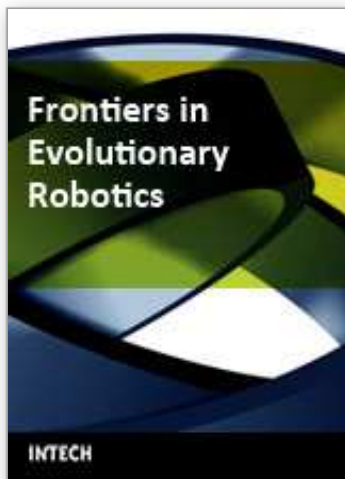
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This book presented techniques and experimental results which have been pursued for the purpose of evolutionary robotics. Evolutionary robotics is a new method for the automatic creation of autonomous robots. When executing tasks by autonomous robots, we can make the robot learn what to do so as to complete the task from interactions with its environment, but not manually pre-program for all situations. Many researchers have been studying the techniques for evolutionary robotics by using Evolutionary Computation (EC), such as Genetic Algorithms (GA) or Genetic Programming (GP). Their goal is to clarify the applicability of the evolutionary approach to the real-robot learning, especially, in view of the adaptive robot behavior as well as the robustness to noisy and dynamic environments. For this purpose, authors in this book explain a variety of real robots in different fields. For instance, in a multi-robot system, several robots simultaneously work to achieve a common goal via interaction; their behaviors can only emerge as a result of evolution and interaction. How to learn such behaviors is a central issue of Distributed Artificial Intelligence (DAI), which has recently attracted much attention. This book addresses the issue in the context of a multi-robot system, in which multiple robots are evolved using EC to solve a cooperative task. Since directly using EC to generate a program of complex behaviors is often very difficult, a number of extensions to basic EC are proposed in this book so as to solve these control problems of the robot.

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