An Optimum Design Algorithm for Mechanisms in Two-Finger Grippers

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Abstract: - In this paper, an analysis of mechanisms in two-finger grippers has discussed to formulate an optimum design procedure. The design problem has been approached and formulated as an optimization problem by using the basic characteristics of grasping mechanisms. A specific case of study has been reported by using 8R2P linkages as a proposed grasping mechanism. Numerical results have been reported with the aim to show the soundness of the new proposed optimum design procedure by referring to computational and practical results.

Key-Words: - Grippers, Grasp Mechanics, Mechanisms, Analysis, Design, Experimental Validation

1 Introduction

In industrial applications a gripper is an important component of industrial robots because it interacts with the environment and objects, which are grasped for manipulative tasks. Usually, a gripper of industrial robots is a specialized devise, which is used to grasp one or a few objects of similar shape, size and weight in repetitive operations, [1-3].

The manipulative operations are usually performed by using two-finger grippers, which are powered and controlled for the grasping action by one actuator only, [4]. In addition, two-finger grippers are used both for manipulation and assembling purposes since most of these tasks can be performed with a two-finger grasp configuration, [5, 6].

The design of a gripper must take into account several aspects for the components and the system together with the peculiarities of a given application or a multi-task purpose. Strong constraints for grasping systems can be considered lightness, small dimensions, body rigidity, multi-task capability, simplicity, and lack of maintenance. These design characteristics can be achieved by considering specific end-effectors or grippers. In the last case a two-finger gripper corresponds to the minimum number of fingers and the minimum complexity of a hand.

Several procedures to design grippers have been reported in literature, as for example [3, 7, 8].

A large number of existing grasp algorithms have been proposed in literature. In [9] existing algorithms have been reported to solve an unconstrained linear programming problem where an objective function represents one or more of the currently known dexterity measures. In [10] an optimal control of fingertip force during grasping operation has been reported as based on fuzzy logic. In [11] multiple performance criteria both at the finger and hand levels have been used to generate a preliminary grasp and then an optimum grasp. In [12] a new genetic algorithm for solving nonlinear multi-criterion optimization problem has been described. In [13] an optimum design procedure and validation testing have been developed for mechanisms of two-finger grippers. In particular, an optimization problem has been formulated by taking into account both the kinematics and statics of the gripper action. In [14] a simple and efficient procedure for optimum dimensional synthesis of grasping mechanisms has been presented. The proposed design has been based on a suitable formulation of grasping performance of grasping mechanisms by using natural coordinates. In [15] a design optimization problem of robot grippers has been formulated by taking into account six objective functions and several constraints. In [16] an optimal grasp planning and dynamic force distribution has been formulated for multi-fingered grasping.

In this paper, performance criteria are investigated and the synthesis problem has been approached and formulated as an optimization problem by using basic characteristics of grasping mechanisms. A suitable algorithm has been developed for a general optimum synthesis of grasping mechanisms by taking into account four objective functions and several constraints. A detailed analysis and results can be found in [17]. A specific case of study has been reported by using 8R2P linkages as a proposed grasping mechanism. Numerical results have been obtained and reported in order to show the efficiency of the proposed new optimization algorithm.

2 The Grasp Problem

Among all the problems encountered in designing robots, the most crucial one concerns the end-effectors. Basic features for a gripper depend strongly of the grasping mechanism. Thus, factors can be considered before choosing a gripper mechanism as following: 1) characteristics of the gripper, which include: maximum payload, dimensions, orientations, number of the composed links; 2) characteristics of the objects, which include: weight, body rigidity, nature of material, geometry, dimensions, condition, position and orientation, contact surfaces, forces acting on the object, environmental conditions; 3) gripper technology; 4) flexibility of the gripper, whether it allows rapid replacement, or easy adjust and external modification, or adaptation to a family of objects contained within a range of specifications; 5) cost and delay that can be involved in design, production, robot operation and maintenance.

Those characteristics are fundamental from a practical viewpoint for the grasping purpose because a dimensional design of grasping mechanisms may have great influence regarding to maximum dimensions of the grasped object, and on the grasping force, [1-3, 8].

The basic components of a two-finger gripper are, [14], Fig.1: fingers, which are the elements that execute the grasp on objects; finger tips, which are directly in contact with a grasped object; grasping mechanism, which is the transmission component between the actuator and the fingers; actuator, which is the power source for the grasping action.

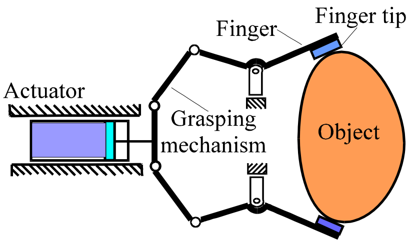

Fig.1 A scheme for mechanical design of two-finger grippers.

To execute a specific grasping task a design problem consists in selecting a proper gripper mechanisms and analizing its kinematics design.

Two types of motion for fingers can be obtained by grasping mechanisms, namely swinging and parallel motions. During a swinging motion a finger rotates to grasp an object, whereas during the parallel motion a finger translates so that a finger maintains its orientation with respect to a fixed frame.

In general, a parallel motion is preferable because it ensures a constant grasp configuration avoiding squeezing forces, but swinging motion could be convenient in the case of larger grasping capability. The choice can be obtained by looking at specific characteristics of specific application in terms of grasping accuracy and grasping capability.

Two-finger grippers are largely used because two-finger grasp can be sufficient in most of the grasping operations. A fundamental characteristic of a two-finger gripper can be recognized in performing a planar grasp.

Schemes in Fig.2 summarize the two-finger grasp of an object by emphasizing on phases with impacts. In particular, the grasping action can be sub-divided in following phases, as proposed in [14]: in Fig.2a) one finger impacts the object and starts the grasping while the fingers move to close onto the object with an approaching motion; in Fig.2b) a finger pushes the object against the other finger while the gripper continues to close onto the object; in Fig.2c) an impact of both the fingers with the object concludes the approaching and pushing motion to a static grasp.

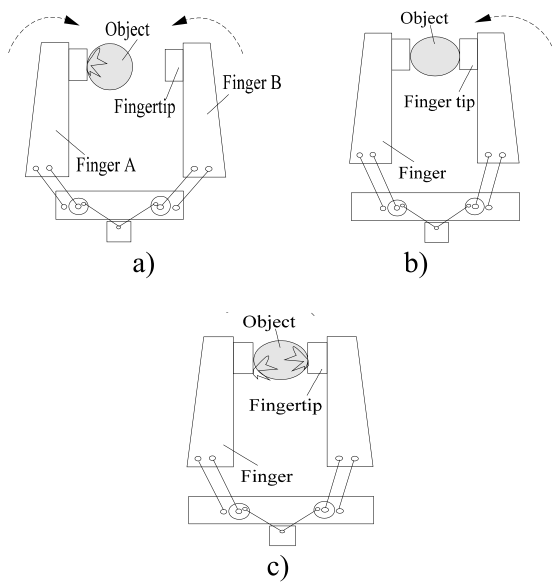

Fig.2 Models of impacts in the grasping phases for a two-finger gripper: a) first impact between finger and object; b) pushing against the other finger; c) final grasp impact by both fingers.

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3 Design Problems

The design problem for grippers consists of sizing all the components of the gripper in order to ensure suitable grasping performances for a proper grasping manipulation. A design procedure can be subdivided in the following steps, [17]: 1) to determine the basic characteristics of the grasped object, in terms of: dimensions, weight, shape, material, density, delicateness; 2) to individuate the environments in which the object should be grasped; 3) to evaluate the required grasping force as a function of maximum dimension of the grasped object; 4) to design finger tips and their sensors; 5) to design a control algorithm; 6) to choose a chain type and to size the grasping mechanism and its operation; 7) to size the actuator by considering the efficiency of the grasping mechanism; 8) to design all the components needed to control the gripper operation.

Thus, at step 1 the geometry, dimensions and delicateness of the grasped object must be analyzed.

At step 2, an individuation of the grasped area is necessary in order to plan all the movement of the gripper during the grasped operation.

At step 3, the model and formulation of the grasp are elaborated in order to evaluate the maximum grasping force, by using a mechanical viewpoint and/or static equilibrium.

At step 4, the shape and size of the finger tips can be obtained as a function of the shape, size and delicateness of the objects. Proper sensors can be chosen, designed and installed on the finger tips depending of a proper finger motion.

At step 5, the control can be designed as depending to the level of grasping force regulation, which is required for the grasped operation.

At step 6, a chain type and grasping mechanism must be chosen by atlas, books, catalogs of existing industrial grippers, and expertise of a designer. The dimensional design can be approached by using traditional techniques for dimensional synthesis of mechanisms. Alternatively, an optimum design of a grasping mechanism can be approached by using commercial tool for PC.

At step 7, it is possible to size and choose the actuator of the grasping mechanism by considering input motion and operation velocity.

At step 8, the design of all the components are sized as fuction of actuator performances, grasping mechanism and control grasping force.

In general, a design of two-finger gripper can be expressed explicitly through suitable formulations of each aspect to give an analytical system of design equations which express the relations between all the components.

The design parameters can be summarized as link sizes l_i, i=1, 2, …, N in which N indicates the number links; configuration angles ϑ_j, j=1, 2, …, M in which M is the number of joint driving mechanism; actuation force Q; characteristics of the control systems as K_P, K_D, K_I, proportional, derivative and integrative gains, respectively.

4 Optimality Criteria

An optimum design procedure can be considered by means the following steps: 1) identification of design constraints and performance characteristics for a given application; 2) formulation of basic performances; 3) analysis of optimality criteria through numerical algorithms; 4) formulation of a single and/or multi-objective optimization problem for design purposes; 5) numerical solution for the multi-objective optimization and interpretation of results; 6) determination of a design solution through a suitable model; 7) mechanical design of all the components and details.

In this paper, we have addressed attention mainly to the design step 3 that is related to optimality criteria, and an optimum design procedure has been proposed using a multi-objective optimization problem in terms of grasping index PI, dimensions, acceleration and velocity of the grasping mechanism.

An optimum synthesis is useful to find the mechanism that has the better efficiency which is variable with the configuration adopted by the mechanism. Thus, the optimum solution should have a small variation of the efficiency in the whole range of objects that can be grasped. In order to satisfy the proposed requirements and to consider an expression for the mechanical efficiency, the grasping index PI can be defined as proposed in [14] in the form

$$PI = \frac{F_{GA} \cos\psi}{Q} \tag{1}$$

where Q indicates the actuating force, F_{GA} is the grasping force applied to the contact point S and ψ is the angle grasp configuration. The grasping index PI can be very useful and easy in evaluation for several grasping mechanisms by using a principle of virtual work. In order to optimize a gripper mechanism, one can define the following optimality criterion, [17]

$$f_1 = PI \tag{2}$$

The number of the links affects the dimension and weight of the device. Minimizing the dimension of the gripper can be useful to reduce its weight and costs and to provide better clearances in a specific workstation, [18]. In order to optimize the gripper mechanism, one can define the following optimality criterion, [17]

$$f_2 = \sqrt{\sum_{i=1}^{N} l_i^2} \quad (3)$$

The acceleration of the gripper should not be so great because it causes inertia phenomenon which may increase the disturbance acting on the grasped object during a grasp. In order to optimize the gripper mechanism, one can define the following optimality criterion, [17]

$$f_3 = \frac{acc_{max} - acc_{min}}{acc_{med}} \quad (4)$$

where acc_{max}, acc_{min} and acc_{med} indicate the maximum, minimum and average acceleration during the grasping action, respectively.

The velocity of the gripper should be constant in order to avoid sudden variation of vibrations and external disturbances during the grasped object. In order to optimize the gripper mechanism, one can define the following optimality criterion, [17]

$$f_4 = \frac{vel_{max} - vel_{min}}{vel_{med}} \quad (5)$$

where vel_{max}, vel_{min} e vel_{med} indicate the maximum, minimum and average velocity during the grasping action, respectively.

The purpose of the above proposed formulation is to simplify the required computations and reduce the overall computational cost for gripper optimization by giving also the possibility to a designer to understand and guide the computational evolution in a numerical technique for optimization problem solution.

5 A Formulation for Optimum Design

The optimization of robot grippers consists in finding the size of grasping mechanism in order to satisfy and optimize constraints and objective functions.

A design formulation can be expressed in the form of multi-optimization problem as

$$\min \quad \mathbf{F}(\mathbf{x}) \quad (6)$$

subject to

$$\begin{aligned} g_1 &= \text{Min } X_S \geq \min X_{S0} \\ g_2 &= \text{Min } Y_S \geq \min Y_{S0} \\ g_3 &= \text{Max } X_S \leq \max X_{S0} \\ g_4 &= \text{Max } Y_S \leq \min Y_{S0} \end{aligned} \quad (7)$$

where $F_i = f_i$ is the i-th component of the vector **F** as a function of the design variables in vector **x**.

The design constraints defined in Eqs.(7) are expressed in term of area that can be reached by the contact point S in the finger tip. If the mechanism is symmetric only one finger mechanism can be analysed, and this area can be defined by the given co-ordinates Min X_S, Max X_S, Min Y_S and Max Y_S of a generic contact point S in a fixed frame. The minimum and maximum values of the co-ordinates of contact point S can be computed as $\min X_{S0}$, $\max X_{S0}$, $\min Y_{S0}$ and $\min Y_{S0}$, respectively.

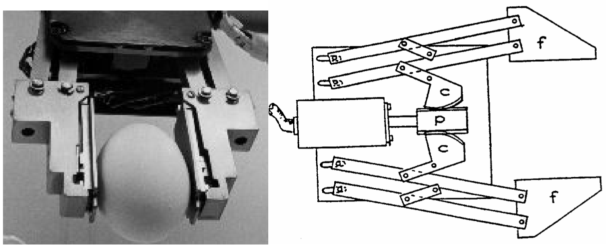
6 A Case of Study

The proposed procedure has been successfully tested through a numerical example by referring a specific case of study with the aim to illustrate the soundness of the optimum design formulation, [17].

A specific mechanism chain has been chosen by considering an 8R2P linkage, Fig.3a). The parallel motion of each finger f is provided by means of 8R2P whose input motion is given by the same double acting pneumatic piston which drives two input cranks c through the rack-pinion gear sector, Fig.3b). Figure 4 shows the related kinematic chain.

Referring to the scheme in Fig.4, the structural parameters of 8R2P linkage are: l_0, l_{01}, l_1, l_{11}, l_2, l_3, l_{22}, l_5, link lengths; l_4 finger link length; h_1, h_2, h_3, slider joint offset; g horizontal offset between slider joints; γ finger link angle between l_3 and l_4; ϑ_1, ϑ_2, ϑ_{11}, ϑ_{22} link horizontal angles with respect to the frame; β link horizontal angle between l_5 and X-axis; ψ link horizontal angle between l_4 and X-axis.

The action of the piston is described by the mobility range of the input angle is ϑ_1. The finger is sketched by the link l_3-l_4.



a) b)

Fig.3 An IBM-7565 gripping device, [19]: a) a view; b) mechanical design, [20].

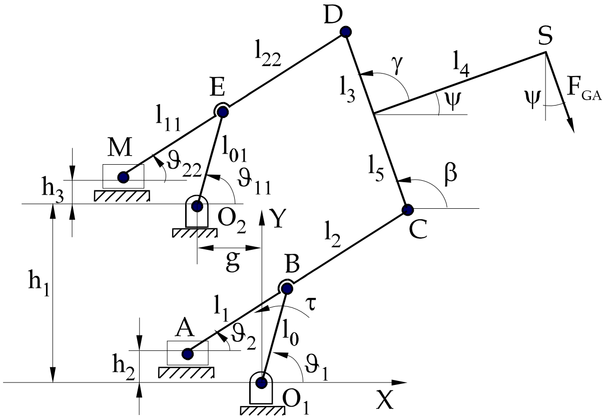


Fig.4 Kinematic scheme of each finger of Fig.2 and their structural parameters.

A point S is assumed to be attached on the extremity of the finger link l_4.

The analysis of the kinematic characteristics of these mechanisms can be obtained by applying a closure equation for the 8R2P linkage referring to the fixed frame O_1XY, Fig.5.

In particular, Fig.5a) shows the trajectory that is described by contact point S during the grasping action; Fig.5b) shows the velocity of point S during the grasping action; Fig.5c) shows the acceleration of point S; Fig.5d) show the variation of IP with respect the input angle ϑ_1, [17].

7 A NUMERICAL EXAMPLE

Equations (1) to (8) have been used in order to optimize the design procedure developed by using the routine “minimax” of Matlab Optimization Toolbox, [21], [17].

The design parameters have been chosen as $l_0 = l_{01}$= 1.8 u, $l_1 = l_{11}$= 3.0 u, $l_2 = l_{22}$ = 12.0 u, l_3 = 1.4 u, l_4 = 7.0 u, l_5 = 0.1 u, h_1 = 1.4 u, $h_2 = h_3 = g$ = 0 u, γ = 0 deg. (Lengths are expressed in u unit and angles in degrees).

Referring to Fig.6, the inequality constraints have been chosen, referring to Eqs.(7) as $minX_{S0}$ = 18 u, $minY_{S0}$ = -4.5 u, $maxX_{S0}$ = 20.5 u e $maxY_{S0}$ = 8 u, respectively.

The results of the proposed case of study are shown in the plots of Figs.7 to 10.

In particular, Figures 7 show the evolution of the multi-objective functions versus the number of iteration. It is worth noting that the optimization algorithm has converged very rapidly to an optimum solution in 76 iterations as reported in Table 1.

Figure 8 shows the evolution of the design parameters versus the number of iterations whereas Table 2 shows the numerical results related to the design parameters.

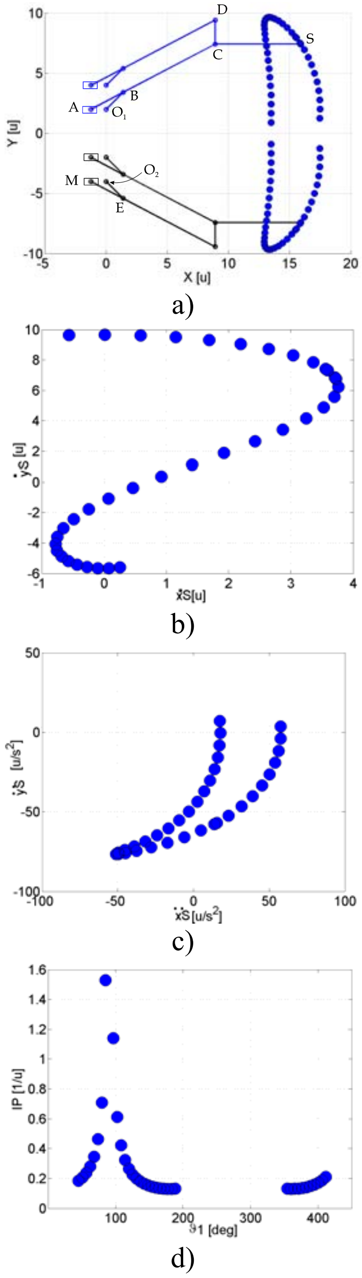


Fig.5 Kinematic characteristics of 8R2P mechanism in Fig.3, [17]: a) path described by point S; b) velocity of point S; c) acceleration of point S; d) IP versus ϑ_1.

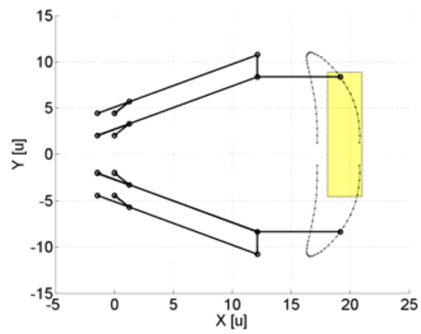


Fig.6 A prescribed working area for the two-finger gripper.

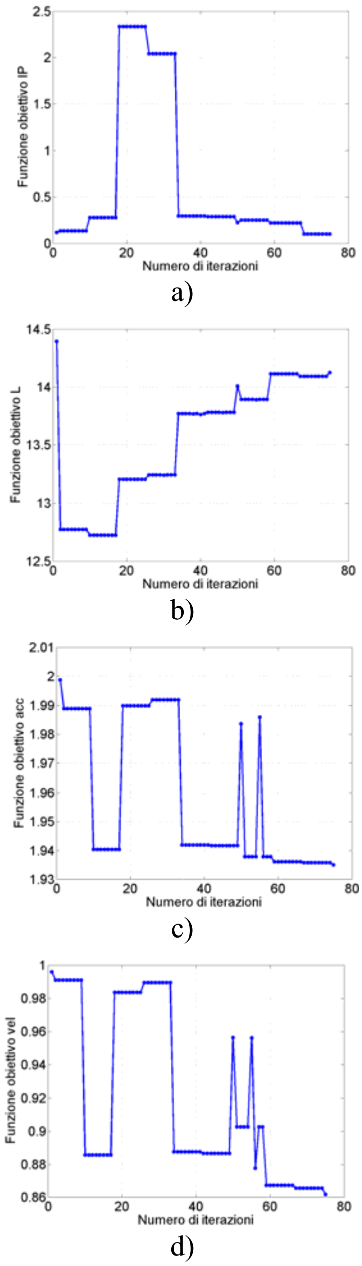


Fig.7 Evolution of the objective functions versus number of iterations in Table 1: a) f_1; b) f_2; c) f_3; d) f_4.

Figure 9 shows the evolution of the constraints versus the number of iterations, whereas Table 3 shows the numerical results related to the constraints. In particular, Fig.9a) shows the evolution of two significant constraints g_1 and g_2 during the optimization process to illustrate how fast and accurately the constraints have been satisfied.

Similarly, Fig.9b) shows the evolution of two significant constraints g_3 and g_4 during the optimization process. In particular, it has been show how fast and accurately constraint g_3 has been satisfied.

Figure 10 shows the optimum kinematic chain

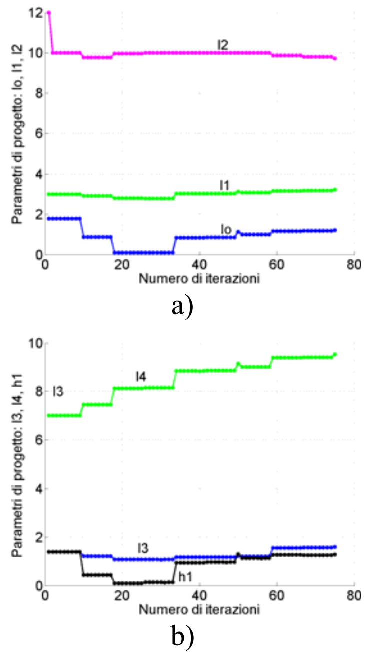


Fig.8 Evolution of the design parameters versus number of iterations for the case of study in Table 2: a) l_0, l_1, l_2; b) l_3, l_4, h_1.

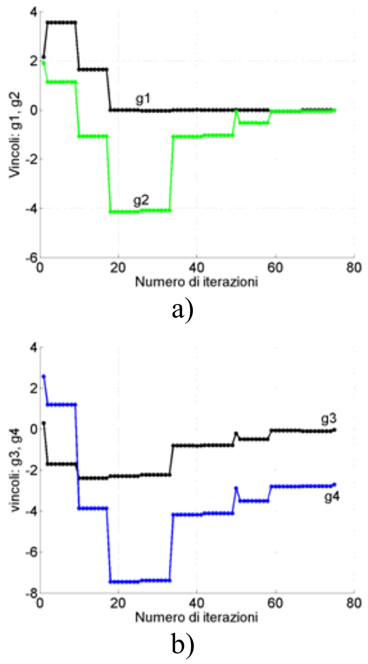


Fig.9 Evolution of the constrains versus number of iterations for the case of study in Table 3: a) g_1, g_2; b) g_3, g_4.

obtained by considering the optimum design parameters that is in Table 2.

In particular, Fig.10a) shows the path described by contact point S. Figure 10b) shows the related obtained working area with respect the imposed constraints as sketched by a rectangle which shows how accurately constraints have been satisfied.

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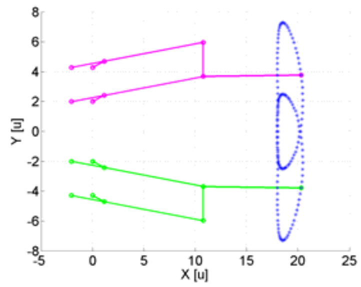
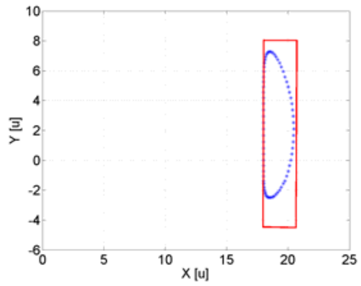


a)



b)

Fig.10 Kinematic scheme of 8R2P mechanism: a) optimal solution; b) optimal working area with respect the prescribed one.

Table 1 Optimal values of objective functions.

Solution	f_1	f_2	f_3	f_4	no. iteration
Guess	0.117	14.40	2.00	0.99	-
Optimal	0.101	14.13	1.93	0.86	76

Table 2 Optimal values of design parameters.

Design parameters	l_0 [u]	l_1 [u]	l_2 [u]	l_3 [u]	l_4 [u]	h_1 [u]
Guess	1.80	3.00	12.00	1.40	7.00	1.40
Optimal	1.23	3.23	9.71	1.59	9.52	1.28

Table 3 optimal values of constraints.

Constraints	g_1 [u]	g_2 [u]	g_3 [u]	g_4 [u]
Guess	2.15	1.90	0.30	2.57
Optimal	0	0	-0.04	-2.71

8 CONCLUSIONS

In this paper we have proposed an optimum design procedure for mechanisms in two-finger gripper.

In particular, a design formulation is proposed as based on basic characteristics of gripper operation such as efficiency, dimension, acceleration and velocity of the grasping mechanisms. By taking into account the above-mentioned characteristics, a new optimization problem has been formulated in terms of a multi-objective optimization problem subject to geometrical constraints.

A case of study has been presented in the form of designing a gripper mechanism by using an 8R2P linkage.

Numerical results have been reported to show the soundness of the proposed new optimum design procedure by referring to computational and practical results.

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