# AN OPTIMUM DESIGN PROCEDURE FOR TWO-FINGER GRIPPERS: A CASE OF STUDY

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ABSTRACT – In this paper we have focused the attention on the dimensional synthesis of the mechanisms in two-finger grippers, that we have named as gripping mechanisms to emphasize on their basic gripping purpose. The design problem has been approached and formulated as an optimization problem by a proposed formulation for the basic characteristics of gripping mechanisms. A case of study has been reported as a numerical example to show the soundness of the proposed optimum synthesis procedure by referring to computational and practical results.

## INTRODUCTION

The two-finger grasp is extensively used both for human and industrial grip, (Pham and Heginbotham, 1986), since it may be considered the simplest efficient grasping configuration.

Most of the gripping systems that are installed in industrial automations and robots are mechanical two-finger grippers, (Belforte, 1985; Pham and Heginbotham, 1986). They are used both for manipulation and assembling purposes since most of these tasks can be performed with a two-finger grasp configuration, (Potter, 1985; Taylor and Swarz, 1955). A gripper can be considered as a critical component of automated manipulations since it interacts with the environment and particularly with the piece to be machined or manipulated so that the gripper gives a great contribution to a practical success of using an automated or robotized solution. Therefore, a good design of a gripper may be of fundamental importance.

The design of a gripper must take into account several aspects of the components and the system together with the peculiarities of a given application or a multi-task purpose. Strong constraints for the gripping system can be considered lightness, small dimensions, 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 an hand.

This means that a good design of a two-finger gripper requires to take into account several problems, (Chelpanov and Kolpashikov, 1983; Chen 1982; Tanie, 1985; Ceccarelli 1994), whose understanding

and consideration are used in this paper with a designing aim.
In this paper we have focused the attention on the dimensional synthesis of the mechanisms in two-finger grippers, that we have named as gripping mechanisms to emphasize on their basic gripping purpose. In particular, some peculiarities of the gripping mechanisms have been considered with the aim to deduce a useful analytical formulation. Then, the synthesis problem has been approached and formulated as an optimization problem by the proposed formulation by using the basic characteristics of gripping mechanisms. A suitable algorithm has been developed for a general optimum synthesis of gripping mechanisms starting from previous experiences reported in (Deibe et al., 1997; Ceccarelli 1997).
A case of study has been investigated and reported as a numerical example in the paper to show the soundness of the proposed optimum synthesis procedure by referring to computational and practical results.

## THE OPTIMUM DESIGN PROBLEM FOR TWO-FINGER GRIPPERS

Industrial applications in structured environment may not require sensorial means so that a gripper structure may be simplified as sketched in Fig.1. Therefore the basic components of a two-finger gripper are, Fig.1: shaped fingers; gripping mechanism; connecting transmissions; actuator.
The mechanical part of a two-finger gripper can be considered as composed by, Fig.1:
- fingers and finger tips, which are the elements in contact with a grasped object, so that they perform the mechanics of grasp on the object itself;
- gripping mechanism, which is the transmission component between the actuator and the fingers;
- actuator, which is the power source for the grasping action of a gripper.

Basic features for a gripper are related to capability for the grasping forces and grasp size. In fact the above-mentioned characteristics are fundamental from a practical viewpoint for the grasping purpose, since they may describe the range of exerting force on the object by the fingers and the size range of the objects which may be grasped.
Thus, a dimensional design of gripping mechanisms may have great influence on the capability D of a gripper, Fig.1, and on the grasping force, since the mechanism size may affect the grasp configuration and transmission characteristics of the device. These peculiarities can be considered well known when it is taken into account the great variety of mechanisms which have been used and are still used as

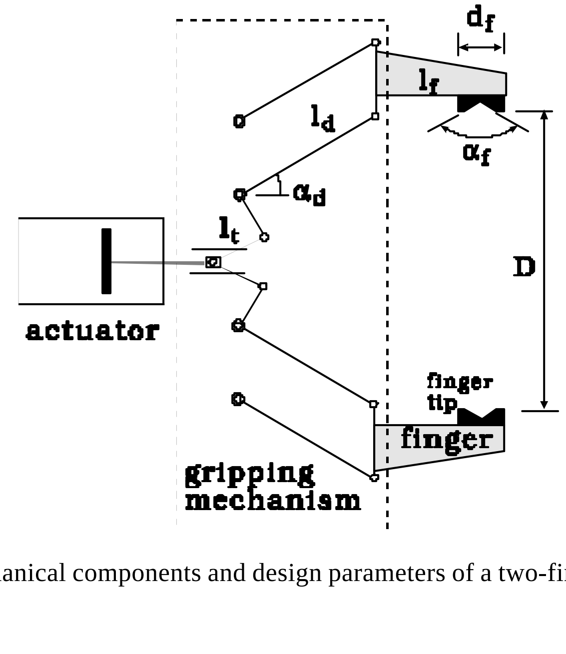


Fig.1. Mechanical components and design parameters of a two-finger gripper.

gripping mechanisms, (Chen 1982; Belforte 1985).
However, we believe that a proper formulation of the design problem for gripping mechanisms may also help for an optimum use of the gripping mechanisms, since a suitable synthesis can give optimum characteristics with respect to the gripping purpose, (Ceccarelli, 1994).
Since the main purpose of a two-finger gripper can be recognized in performing a planar grasp, some fundamental design considerations may be deduced by approaching a two-finger grasp and its mechanics, (Ceccarelli and Nieto, 1993).
Referring to Fig.2, a configuration of two-finger grasp can be characterized by possible elementary motions of a grasped object among the fingers as: slipping down along a direction which is orthogonal to a plane of the gripping forces exerted by the fingers as couplers of mechanisms; squeezing which may occur in sliding outward or inward to the gripper itself due to an effect of force components pushing the object (in this case an increase or a decrease of the gripping force by fingers may produce a squeezing motion or a release of the object); rolling about the squeezing line and winding about the slipping line consisting in a motion of revolution of the object among the fingers due to an external torque or a force couple of $F_A$ and $F_B$; whirling about the contact line which can be also due to a torque by the object's weight when its mass center does not lay on the contact line yet.
Although two contact-points cannot considered enough even for a planar grasp, a two-finger gripper can perform a suitable grasp when force constraints are taken into account so that four conditions can be achieved for a firm grasp. In addition, all the above mentioned elementary motions of the object may be avoided when suitable grasping force $F_A$ and $F_B$ are exerted by the fingers so that friction forces may arise to completely balance the external action on the object.
However, for sake of simplicity and because indeed the difference in position can be very small, the grasping forces can be thought with a common value **F**. Same observations can be developed for the friction evaluation at the points A and B through the coefficients $\mu_A$ and $\mu_B$, which can be assumed with a common value $\mu$. The angles $\varphi_A$ and $\varphi_B$ represent the angles of the friction cones at the contact points A and B, respectively, and they are related to the friction coefficients by $\mu_A = \tan \varphi_A$ and $\mu_B = \tan \varphi_B$. The grasping configuration of the object with respect to the fingers gives the angles $\psi_A$ and $\psi_B$,

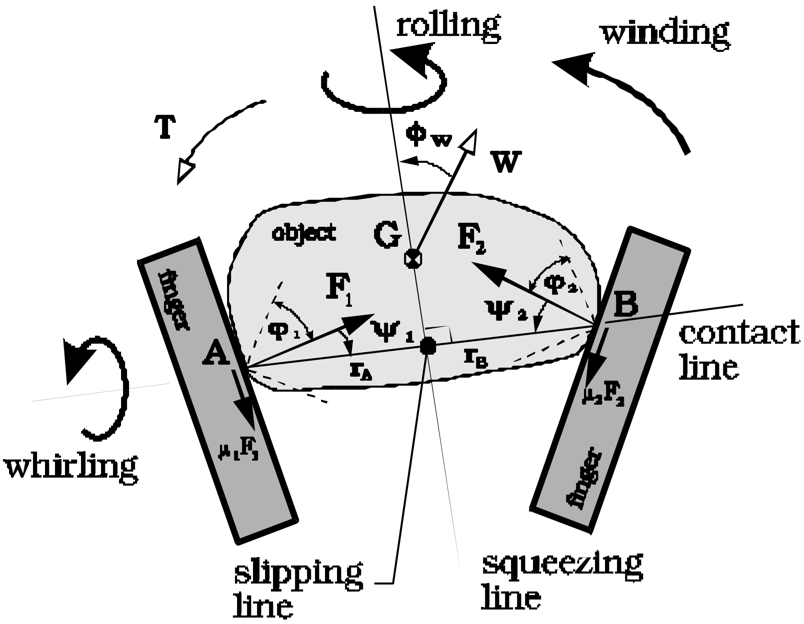


Fig.2. A mechanical model for a two-finger grasp.

which strongly depend on the orientation of the fingers, the position of the contact points, and the shape of the object and the fingers.
Although the contact points, which define the contact line as a line joining them, Fig.2, can be located in the same relative position on the fingers, the angles $\psi_A$ and $\psi_B$ can differ from each other. However, because of the symmetry of a two-finger gripper, in a design procedure it is convenient to assume them as equal to the most unfavorable value $\psi$, which refers to the case that gives a squeezing component from the grasping force itself.
In Fig.2 a planar grasp by two fingers has been modeled by using the above-mentioned considerations. In addition, $r_A$ and $r_B$ represent the distances of A and B, respectively, from the squeezing line; $r_G$ is the distance of G from the contact line; **W** is the weight of the object and it is oriented with an angle $\Phi_W$ with respect to the squeezing line. **T** is an external torque acting on the object, and it includes the inertial actions due to the manipulator movement, as well as **W** may include the inertial and external forces, so that the model of Fig.2 can describe all the situations, which may occur to an object grasped by a two-finger gripper.
The basics of the static equilibrium of the grasped object can be expressed by using the model of Fig.2 along the directions of the contact and the squeezing lines in term of forces as

$$\begin{aligned} &F_A \cos\psi_A - F_B \cos\psi_B + \mu_A F_A \sin\psi_A - \mu_B F_B \sin\psi_B + W \sin\Phi_W = 0 \\ &F_A \sin\psi_A + F_B \sin\psi_B - \mu_A F_A \cos\psi_A - \mu_B F_B \cos\psi_B + W \cos\Phi_W = 0 \end{aligned} \qquad (1)$$

and in term of torque as

$$T - r_G W \sin\Phi_W - r_A F_A (\sin\psi_A - \mu_A \cos\psi_A) + r_B F_B (\sin\psi_B - \mu_B \cos\psi_B) = 0 \qquad (2)$$

Indeed, the directions of the friction forces, and consequently their signs in the Eqs.(1) and (2), will be determined to be contrary to the relative motion between the object and the finger. Dynamic variations can be modeled by assuming **T** and **W** variable as a function of the motion of the gripper and object.
The above-mentioned design models and performance considerations address great importance to the gripping mechanism since it transmits the motion and force to the fingers for a suitable grasp. In addition, such considerations may strongly suggest to use a design formulation for gripping mechanisms in the form of an optimization problem as

$$\max\ f \qquad (3)$$

subject to

- design constraints
- object characteristics
- peculiarities of the application

The critical point of such a design formulation is the choice of a suitable objective function $f$, which may include the peculiar aspects of the gripping mechanism together with its design parameters, and may give a solvable numerical formulation in a sense of obtaining solutions which are not trivial. The constraints can be expressed for so many and different characteristics but they should be analytically formulated. This may limit the constraints to be considered into the design problem (3).
Further complications may arise in formulating the constraints with the attempt to specialize the mechanism design to a gripping purpose, which nevertheless can be stated as general as well as

specific with respect to an object or a manipulation.
Among the many possible choices, we propose to use as the objective function for a gripping mechanism design the compact expression of the Grasping Index given by (Ceccarelli et al., 1992; Ceccarelli 1994)

$$G.I. = \frac{F_A \cos\psi_A + F_B \cos\psi_B}{P} \tag{4}$$

in which *P* is the force exerted by the actuator. The grasping configuration is considered through $\psi_A$ and $\psi_B$ , and the grasping action by means of $F_A$ and $F_B$.
The objective function can be further simplified by assuming $\psi_A = \psi_B = \psi$, and $F_A = F_B = F$ to give

$$f = \frac{2\,F\cos\psi}{P} \tag{5}$$

Eqs.(4) and (5) take into account both the aspects of force and motion transmission, which can be recognized as fundamental for design and working of a gripping mechanism. Indeed previous experiences for analysis and synthesis purposes, (Deibe et al., 1997; Ceccarelli 1997) have proved the feasibility of the Grasping Index in the form of Eq.(5), since it can be easily formulated analytically for several gripping mechanisms by using the Principle of Virtual Work. In fact, by assuming the friction forces in the joints of a mechanism as negligible, the expression of the efficiency ratio F/P can be conveniently expressed as

$$\frac{F}{P} = \frac{2\left(r'\cos\psi + r\,\psi'\cos\psi\right)}{v_P} \tag{6}$$

in which $v_P$ is the velocity of the actuator, *r*' and $\psi'$ are the position and angular velocity of the fingers. The ratios $r'/v_P$ and $\psi'/v_P$ can be computed by using a velocity analysis of a gripping mechanisms so that the Grasping Index can be evaluated by performing a kinematic analysis only. Moreover, this procedure for a formulation and evaluation of a performance index suggests to use natural coordinates for an easy and general way to formulate and solve the optimum design problem.

## A CASE OF STUDY FOR A NUMERICAL EXAMPLE

The proposed procedure has been successfully tested through a numerical example, which has been reported in the paper to better illustrate the application and feasibility both of the problem formulation and numerical solution technique, also with the aim to stress some design practical considerations.
Fig.3 shows a widely used gripping mechanism. It is a parallelogram linkage with sliders as bottom pairs, which is connected to the actuator through a pinion. Due to the mechanism symmetry, only the left half can be studied. Fig.4 illustrates the mentioned half along with the different magnitudes involved in the problem. The pinion and the crank link A2 are rigidly interconnected. Reference points are numbered from 1 to 8. Design variables of the problem are Cartesian coordinates of fixed points, structural angles and link lengths, so that the vector of design variables is,

$$\begin{aligned} b^t = \{ & x_A \quad x_B \quad y_B \quad \alpha_o \quad L_{A2} \quad L_{B5} \quad x_C \quad y_C \quad \gamma_C \quad x_D \quad y_D \quad \gamma_D \quad \cdots \\ & \cdots \quad L_{34} \quad L_{23} \quad L_{67} \quad L_{56} \quad L_{47} \quad L_{48} \quad L_{78} \quad \varphi \} \end{aligned} \tag{7}$$

It may be seen in Eq.(7) that the *y*-coordinate of fixed point A does not appear in the vector of design

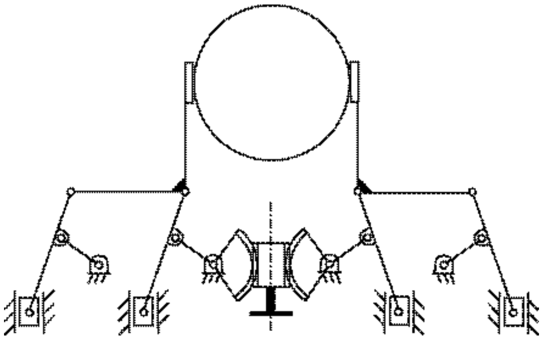

Fig.3. A case of study for the proposed optimum synthesis.

variables. The reason is that $y_A=0$ has been imposed in order to avoid unrelevant vertical translations of the whole mechanism. As it will be seen ahead when constraint equations will be listed, the design variable $\alpha_0$ corresponds to the value of angle $\alpha$ at the closed position of the mechanism. The function of point C and angle $\gamma_C$ (and point D and angle $\gamma_D$) define the position and orientation of their corresponding prismatic joint.

All the distances will be given in mm. For the case of study, the capability has been fixed as *D*=100. The three precision points indicated in Fig.4 are considered: the *open* position, in which the distance between grippers is 2*D*; the *intermediate* position, in which such distance is 1.5*D*; and the *closed* position, in which the distance is just *D*. Distances *HB*, *HT* and *V* limit the total size of the mechanism. For this example, *HB*=60, *HT*=300 and *V*=150, which means that the mechanism should keep inside a rectangle of 300x360. The actuator half-width has been set to *R*=10 and, therefore, the pinion radius can be calculated as $r=-x_A-R$. The stroke actuator, *AS*, has been left free and will be obtained as a result for each optimized mechanism. The reference frame (*x*,*y*) has been defined so that the actuator (point 1) is at (0,0) when the gripper is in the *closed* position.

Therefore, the vector of dependent variables is,

$$q^t=\{y_1^j \quad \alpha^i \quad x_2^i \quad y_2^i \quad x_3^i \quad y_3^i \quad x_4^i \quad y_4^i \quad x_5^i \quad y_5^i \quad x_6^i \quad y_6^i \quad x_7^i \quad y_7^i \quad y_8^i\}$$

*i*=1,2,3; *j*=2,3 (8)

In expression (8), the superindex indicates the corresponding precision point: 1 stands for the *closed* position, 2 for the *intermediate* position and 3 for the *open* position. Some coordinates of reference points are missed since they are automatically known from the problem data as

$$x_1^1=0\,;\; y_1^1=0\,;\; x_8^1=-0.5D\,;\; x_1^2=0\,;\; x_8^2=-0.75D\,;\; x_1^3=0\,;\; x_8^3=-D \qquad (9)$$

The *y*-coordinate of point 1 at the *closed* position, $y_1^3$ is found among the dependent variables because, as already commented, the actuator stroke *AS* has been left free.

In order to obtain the expression of the objective function, the Principle of Virtual Power is applied, which yields (see Fig.4),

$$-P\dot{y}_1-2F_x\dot{x}_8-2F_y\dot{y}_8=0 \qquad (10)$$

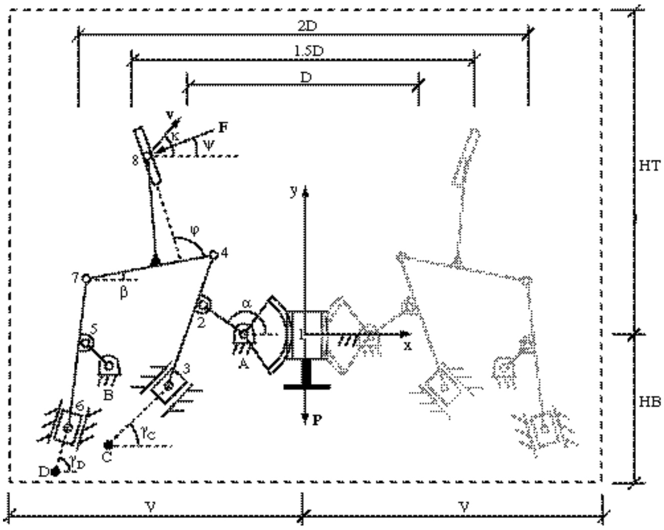


Fig.4. Design parameters for the two-finger gripper of Fig.3.

The angle $\psi$ can be written as a function of the design variable $\varphi$ and the angle $\beta$, which in turn is a function of the Cartesian coordinates of reference points 4 and 7, in the form

$$\psi = \beta + \varphi - \frac{\pi}{2} \tag{11}$$

Therefore, if $F_x$ and $F_y$, the Cartesian components of the grasping force **F**, are substituted in terms of the force modulus *F* and the angle $\psi$, Eq.(10) turns into,

$$-P\dot{y}_1 - 2F\dot{x}_8 \cos\psi - 2F\dot{y}_8 \sin\psi = 0 \tag{12}$$

and rearranging terms,

$$\frac{P}{2F} = -\frac{\dot{x}_8 \cos\psi + \dot{y}_8 \sin\psi}{\dot{y}_1} \tag{13}$$

Now, dividing both sides by the factor $\cos\psi$,

$$\frac{P}{2F\cos\psi} = -\frac{\dot{x}_8 + \dot{y}_8 \tan\psi}{\dot{y}_1} \tag{14}$$

It may be seen that the left-hand-side of Eq.(14) is the inverse of the Grasping Index. This quantity, which could be called *I.G.I.* (Inverse of the Grasping Index) will be used in the optimization process as objective function instead of *G.I.* for the sake of clarity (reasons will be given ahead). It is obvious that *I.G.I.* can be easily evaluated by performing a velocity analysis of the mechanism with $\dot{y}_1 = -1$, thus yielding,

$$\text{I.G.I.} = \frac{P}{2F\cos\psi} = \left(\dot{x}_8 + \dot{y}_8 \tan\psi\right)_{\dot{y}_1=-1} \tag{15}$$

Therefore, the objective function of the optimization problem can be assumed as

$$f = \sum_{i=1}^{npp} w_i \left(\text{I.G.I.}\right)_i = \sum_{i=1}^{npp} w_i \left[\frac{P}{2F\cos\psi}\right]_i = \sum_{i=1}^{npp} w_i \left[\left(\dot{x}_8 + \dot{y}_8 \tan\psi\right)_{\dot{y}_1=-1}\right]_i \tag{16}$$

where *npp* stands for the number of precision points, and $w_i$ are the weight factors for each precision point. In this example, $npp = 3$ and $w_1 = w_2 = w_3 = 1/3$. During the optimization process, *f* must be made minimum. Then, to evaluate the objective function, so many velocity analysis of the mechanism as precision points should be carried out.
The equality constraints of the problem, **h**, are the following,

$$\begin{aligned}
& r\left(\alpha^i - \alpha_o\right) - y_1^i = 0 \\
& x_2^i - x_A - L_{A2}\cos\alpha = 0 \\
& y_2^i - y_A - L_{A2}\sin\alpha = 0 \\
& \left(x_3^i - x_C\right)\sin\gamma_C - \left(y_3^i - y_C\right)\cos\gamma_C = 0 \\
& \left(x_4^i - x_3^i\right)^2 + \left(y_4^i - y_3^i\right)^2 - L_{34}^2 = 0 \\
& L_{34}\left(x_2^i - x_3^i\right) - L_{23}\left(x_4^i - x_3^i\right) = 0 \\
& L_{34}\left(y_2^i - y_3^i\right) - L_{23}\left(y_4^i - y_3^i\right) = 0 \\
& \left(x_5^i - x_B\right)^2 + \left(y_5^i - y_B\right)^2 - L_{B5}^2 = 0 \\
& \left(x_6^i - x_D\right)\sin\gamma_D - \left(y_6^i - y_D\right)\cos\gamma_D = 0 \\
& \left(x_7^i - x_6^i\right)^2 + \left(y_7^i - y_6^i\right)^2 - L_{67}^2 = 0 \\
& L_{67}\left(x_5^i - x_6^i\right) - L_{56}\left(x_7^i - x_6^i\right) = 0 \\
& L_{67}\left(y_5^i - y_6^i\right) - L_{56}\left(y_7^i - y_6^i\right) = 0 \\
& \left(x_4^i - x_7^i\right)^2 + \left(y_4^i - y_7^i\right)^2 - L_{47}^2 = 0 \\
& \left(x_4^i - x_8^i\right)^2 + \left(y_4^i - y_8^i\right)^2 - L_{48}^2 = 0 \\
& \left(x_7^i - x_8^i\right)^2 + \left(y_7^i - y_8^i\right)^2 - L_{78}^2 = 0
\end{aligned} \tag{17}$$

where again the superindex indicates the precision point, and then Eqs.(17) should be written for *i*=1,…,*npp*. These equality equations assure that reference points and design variables fulfill the kinematic conditions in position at all the precision points established.
Before describing the inequality constraints, a consideration should be pointed out. The objective function at a certain precision point defined in (15) becomes minimum when the velocity **v** of the grasping reference point (point 8) is orthogonal to grasping force **F**. This means that fingers slide along the object and, in such a way, they exert no force on the object. Mathematically, this fact implies that the objective function becomes zero (minimum, of course), but it is not a desirable solution. To avoid this behaviour in the optimization process, the angle between fingers velocity **v** and grasping force **F** is

to be limited to a maximum value.
In addition the inequality constraints **g** can be listed as

$$-V \le x \le 0 \tag{18}$$
$$-HB \le y \le HT \tag{19}$$
$$y_C, y_D < -HB \tag{20}$$
$$0 < L \tag{21}$$
$$0 < \alpha < 2\pi \tag{22}$$
$$0 < \gamma < \pi \tag{23}$$
$$0 < \varphi < \pi \tag{24}$$
$$0 < \dot{x}_8^i,\ i=1,\ldots,npp \tag{25}$$
$$\text{limit} < \left|\cos\left(\kappa^i - \psi^i\right)\right|,\ i=1,\ldots,npp \tag{26}$$

Eq.(18) indicates that all the *x*-coordinates of the reference and fixed points at the different precision points, must keep in the range [-*V*,0]. Similarly, Eq.(19) implies that all the *y*-coordinates of the reference and fixed points at the different precision points, must keep in the range [-*HB*,*HT*]. The objective of Eq.(20) is to prevent points C and D from becoming coincident with their corresponding counterparts, points 3 and 6 respectively, thus leading to nonsense constraint equations for the prismatic joints. Eq.(21) is set to avoid negative values for the lenghts of the links, although a minimum acceptable positive value might have been imposed too. Eqs.(22) to (24) establish the limits of the different angles. Eq.(25) forces the gripping mechanism to move in the correct half plane. Eq.(26) assures that finger velocity **v** and grasping force **F**, keep as parallel as the analyst desires, thus supressing the danger of the abovementioned trivial solution. For this example, *limit*=0.8.
The goal of the optimization process is to make minimum the objective function *f*. Obviously, the minimum possible value of *f* is zero. However, *f*=0 does not posess in general any physical meaning, as long as it implies an infinite transmission factor in force over a certain range of motion of the mechanism. Moreover, the objective function is minimized at a finite number of precision points, but nothing is imposed at intermediate points. Therefore, a solution which provides a very low value of the objective function could be worse than another with a higher value of the objective function, if the latter behaves better at intermediate points. Problems like branch defect may also appear. In order to evaluate the different optimized solutions, the optimization process will be carried out in several steps. To this end, a partial objective function $f^*$ will be defined for each step:

$$f^* = f - f_o \tag{27}$$

where $f_o$ is the desired value of the objective function *f* at the end of the partial optimization process. In this way, different optimized solutions can be obtained, corresponding to different values of the objective function chosen by the analyst.
The described method has been implemented in the Matlab technical environment (Mathworks 1993), where function *constr* has been used for the optimization process. Table 1 shows initial and several optimized values of the design variables. Fig.5 illustrates the corresponding mechanisms.
The four partial solutions presented have been chosen among the infinite possible optimized solutions because they can be representative of the evolution experienced by the optimization process.
Fig.6 shows the values of the objective function along a certain range of motion for the different solutions presented above. The selected range of motion is measured in terms of distance between fingers: it starts at 100 and finishes at 200. Remember that precision points were 100 (*closed* position),

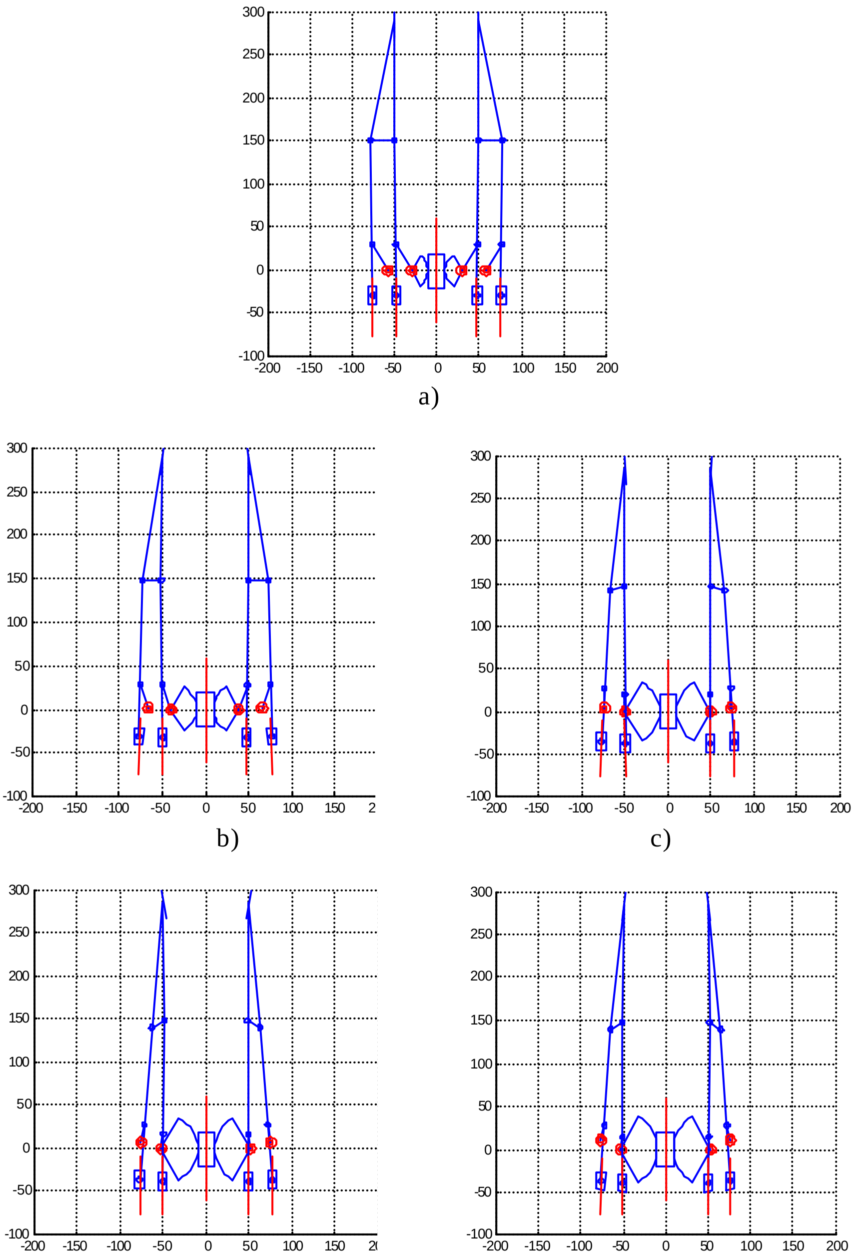


Fig.5. Designed gripping mechanisms: a) initial with f=3.07; b) optimized with *f*=2.0; c) optimized with *f*=1.0; d) optimized with *f*=0.7; e) optimized with *f*=0.5.

150 (*intermediate* position) and 200 (*open* position). It may be seen that the four optimized solutions provide a quite uniform behaviour of the objective function along the entire range of motion.

Solution with *f*=0.5 gives a very small value of *f* at the closed position (*f*=0.03), which means that the mechanism is reaching a dead position and, therefore, danger of branch defect is not far from this solution.

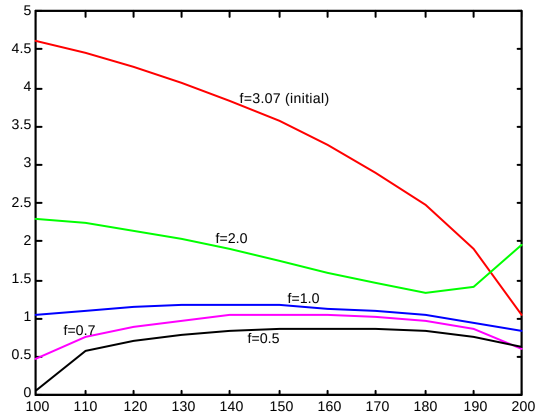


Fig.6. Objective function versus the mechanism motion as distance 8-8'.

Table 1 – Initial and optimized design variables, and other parameters for the mechanisms of Fig.5.

| ***f*** | **3.07 (Init.)** | **2.0** | **1.0** | **0.7** | **0.5** |
|---|---|---|---|---|---|
| $x_A$ | -30 | -38.88 | -49.69 | -51.82 | -53.51 |
| $x_B$ | -58 | -65.83 | -73.51 | -75.43 | -76.53 |
| $y_B$ | 0 | 1.90 | 4.28 | 7.23 | 10.76 |
| $\alpha_0$ | 2.1159 | 1.9340 | 1.5665 | 1.4279 | 1.4013 |
| $L_{A2}$ | 36 | 29.47 | 20.38 | 17.25 | 13.93 |
| $L_{B5}$ | 36 | 28.55 | 23.42 | 20.97 | 17.03 |
| $x_c$ | -48 | -47.77 | -49.07 | -51.08 | -51.76 |
| $y_c$ | -150 | -150.01 | -150.03 | -150.03 | -150.04 |
| $\gamma_C$ | 1.5708 | 1.5785 | 1.5723 | 1.5588 | 1.5627 |
| $x_D$ | -76 | -78.63 | -78.23 | -77.46 | -78.31 |
| $y_D$ | -150 | -150.01 | -150.02 | -150.02 | -150.03 |
| $\gamma_D$ | 1.5708 | 1.5529 | 1.5633 | 1.5690 | 1.5555 |
| $L_{34}$ | 180 | 181.47 | 184.50 | 185.86 | 187.13 |
| $L_{23}$ | 60 | 60.52 | 57.84 | 55.33 | 52.68 |
| $L_{67}$ | 180 | 179.54 | 177.86 | 177.26 | 176.88 |
| $L_{56}$ | 60 | 60.18 | 63.11 | 64.47 | 64.10 |
| $L_{47}$ | 28 | 22.30 | 16.76 | 16.10 | 15.69 |
| $L_{48}$ | 140 | 140.68 | 139.42 | 138.60 | 138.02 |
| $L_{78}$ | 142.77 | 142.86 | 145.17 | 146.40 | 147.11 |
| $\varphi$ | 1.5708 | 1.4296 | 1.3582 | 1.2710 | 0.8775 |
| AS | 16.65 | 26.40 | 46.44 | 57.72 | 67.08 |
| $r$ | 20 | 28.88 | 39.69 | 41.82 | 43.51 |

CONCLUSIONS

In this paper an optimum design for gripping mechanisms of two-finger grippers has been proposed in the form of a suitable optimization problem by using fundamental characteristics of both the grasp action and gripping mechanism performance. The grasping aim for a gripping mechanism has been formulated through a suitable performance index, named as Grasping Index, which may describe synthetically both kinematic and static characteristics for a proper grasp. The proposed formulation has been useful for a numerical procedure which may make easily use of commercial software for solving the optimization problem. A interesting result of this paper can be recognised in the fact that it proposes a way to design mechanisms for grippers by taking into account the peculiarities of required performances in grasping actions.

A case of study has been reported as numerical example to better illustrate practical and numerical aspects of the engineering implementation of the proposed optimum synthesis method.

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