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AN OPTIMUM MULTI-OBJECTIVE PROCEDURE FOR DESIGN OF MICROGRIPPING MECHANISMS

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ABSTRACT- In this paper, the mechanical design of microgrippers has been focused mainly to the dimensional synthesis of the mechanism. The basic gripping purpose and the characteristics of grasped objects have been analyzed to deduce useful formulation also with the help of results of previous experimental experiences. The general formulation based on a multi-criterion design optimization is proposed. In particular, the mechanical efficiency, stiffness and adhesive force characteristics are taken into account for design purposes. The design of a microgripping mechanism for a two-finger microgripper has been reported to show the soundness of the proposed synthesis procedure.

Keywords: Robotics, Microgrippers, Microgripping Mechanisms, Optimum Design.

INTRODUCTION

In many different fields the handled objects are becoming every day smaller and smaller. Therefore, to handle these microobjects new tools are need as pointed out in [1].

Many researchers are stressing this topic by developing new devices that can be used for handling microobjects in many different applications such as industrial microassembly, space microrobotics or microsurgery tasks, [2-5].

The accuracy that can be needed for a micromanipulative task can be of the order of microns; displacement and force capability are usually within very limited range of dN order, in agreement with the dimensions of the handled objects, [2].

A design solution of a microgripper should satisfy some specific characteristics and performance criteria especially as the accuracy and grasp force capability, [2-5]. Then, the design problem can be approached and formulated as an optimization problem.

Optimum design procedures have been developed in many different fields, [6]. In particular, optimum design procedures have been proposed for two finger grippers for example in [7, 8]. Similar procedures have been also proposed for the design of microgrippers in [9].

In this paper, the mechanical efficiency, stiffness and adhesive force characteristics have been taken into account for defining a multi-objective optimum design procedure. The design of a microgripping mechanism for a two-finger microgripper is given to show the soundness of the proposed procedure.

DESIGN CHARACTERISTICS OF MICROGRIPPERS

There are several mechanical constrains for a microgripper can be considered in design such as dimensions, accuracy, displacement, and force capability. These constrains must be defined according to the micro-grasping characteristics that are strictly related to dimensions of the handled objects and kind of micromanipulative task, [2, 9].

The required accuracy can be considered inversely proportional to the geometric dimensions since smaller objects require greater positioning accuracy. The displacement and force capability are directly proportional to the geometric dimensions since bigger objects require larger displacements of fingers and greater grasping force. For these reasons in micromanipulative tasks the needed accuracy is high while displacement and force capability are of small magnitude in agreement with the dimensions of the handled objects, [9]. Therefore, high accuracy is required in tasks like microassembly and microsurgery, which are typical field of application of microgrippers.

The accuracy, displacement and force performances for a microgripper can be defined by using suitable models of a desired manipulation task. In [10], for example, a grasp force modeling and measuring is proposed for two-finger conventional grippers. This approach can be extended in the microworld. Figure 1 shows an example of model for a micro-grasping task of objects whose dimensions are of millimeter order. It is worth nothing that the model in Fig.1 is quite similar to the model proposed in [10], even if important differences must be considered such as the scale of the acting forces and the kind of contact between the object and the fingers.

As regards the scaling of the acting forces, Table 1 can be deduced by using dimensional analysis, similitude laws and experimental measurements as shown for example in [9, 11]. Table 1 illustrates the main forces and their proportionality to the geometric dimension L of a grasped object by using coefficients k_v, k_e, k_G, k_I, k_m, k_c, and k_g that summarize laborious computation through suitable formulation that is given even from experimental results found in the literature.

Moreover, Table 1 show two numerical examples, giving the intensity of different types of forces that have been evaluated in the case of L having a size of one millimeter and one hundred millimeter, by using the above-mentioned proportionality laws. These examples show that, when the grasped object is of millimeter order, forces due to gravity and inertia can be neglected. But even the action of capillarity forces, Van der Waals forces and electrostatic forces can be neglected with respect to the grasping force. It is worthy nothing that these forces give adhesive action between grasped object and fingers of the microgripper. Adhesive forces are helpful in picking and moving an object but, at the same time, they complicate the release of the object as pointed out in [5, 11].

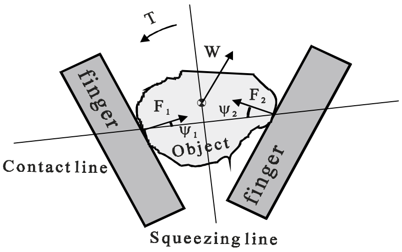


Fig.1 A model for the grasping with a two-finger microgripper.

Table 1 Illustrative value of forces as a function of the dimension L of an iron grasped object.

Law	Type of force	Force [N] (for L=1mm)	Force [N] (for L=100mm)
k_vL	Van der Waals	0.119 k_v=1.19 10^2	1.19 10^{-9} k_v=1.19 10^{-10}
k_eL^2	Electro-static	0.014 k_e=1.40 10^4	1.36 10^{-6} k_e=1.36 10^{-12}
k_GL^3	Gravity	3.00 10^{-5} k_G=3.00 10^4	30.0 k_G=3.00 10^4
k_IL^4	Inertia	3.06 10^{-9} k_I=3.06 10^3	0.306 k_I=3.06 10^3
k_mL^4	Magnetic force	1.00 10^{-6} k_m=1.00 10^5	1.00 10^{-1} k_m=1.00 10^5
k_cL	Capillarity	0.458 k_c=4.58 10^2	0.229 k_c=2.29 10^{-2}
k_gL	Grasping force	1 k_g=1 10^3	300 k_g=3 10^3

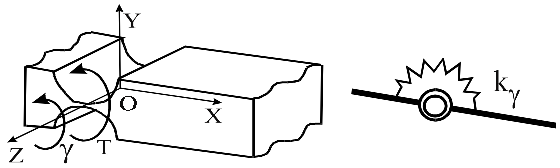
The grasping force is the force that the fingertips can apply on the grasped object. The intensity of this force depends on the type and dimension of the microgripping mechanism.

FLEXURAL JOINTS FOR MICROGRIPPERS

The operation of a mechanical microgripper strongly depends on the design and behavior of the microgripping mechanism, which transmits the motion and force to the gripping fingers. Therefore, the first design effort is to define a suitable microgripping mechanism.

Theoretically, a microgripper could have the same mechanism type of a conventional gripper. However, these mechanisms are not always feasible for microgrippers since the small dimensions. In particular, it is worthy nothing that the conventional joints cannot be easily miniaturized. This problem can be solved by using flexural joints. In fact, flexural joints can be manufactured from a single piece of material by using milling machines to provide a monolithic mechanism, which eliminates interface wear and allow very high miniaturization, as pointed out in [12, 13].

Figures 2 a) and b) show a design scheme and a kinematic model for a flexural joint obtained by manufacturing two notches on a single piece of material to have rotations about the Z-axis related with the stiffness parameter k_γ. The stiffness about the X-axis and the Y-axis is much higher then k_γ. Therefore, the rotations about the X-axis and the Y-axis can be neglected and the flexural joint allows only a rotation γ of few degrees about the Z-axis when a torque T is applied. Actual misalignment of the actuation force or any unexpected forces may cause rather large parasitic deflections in other direction than the desired one. However, generally, this is enough for the microworld applications.



a) b)

Fig.2 A flexural joint: a) manufacturing scheme; b) kinematic model.

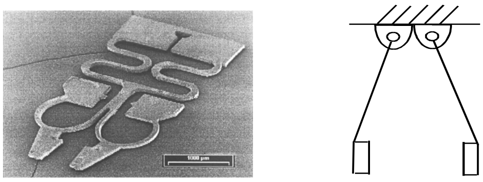
MICROGRIPPING MECHANISMS

The State of Art for two-finger microgrippers shows that usually very simple microgripping mechanisms are used in order to obtain a high miniaturization level.

Illustrative examples are reported in Figs.3 to 5. Figure 3 a) shows the microgripping mechanism of a two-finger microgripper as proposed in [3]. It is made of shape memory alloy metal. The two fingers can be considered rigid and able to rotate about a common point as shown in the kinematic model of Fig.3 b).

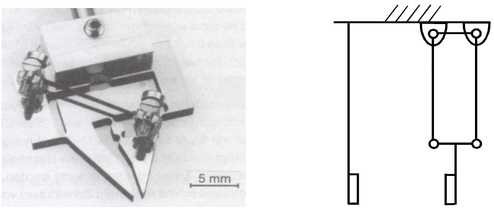
Figure 4 a) shows the microgripping mechanism of a two-finger microgripper as proposed in [4]. It is made of metal and uses one shape memory alloy wire as actuation. One finger of this prototype is fixed, the other finger is made by a four-bar linkage mechanism that allows a rotative motion of the finger as shown in the kinematic chain of Fig.4 b).

The accuracy can be increased using microgrippers are able to grasp objects with a synchronized and parallel motion of the fingers by using two four-bar linkages as shown for example in the prototype of Fig. 5 a), [5], and more clearly in its kinematic chain model of Fig.5 b). This prototype is made of POM (Polyoxymethylen) and uses two shape memory alloy wires as actuation.



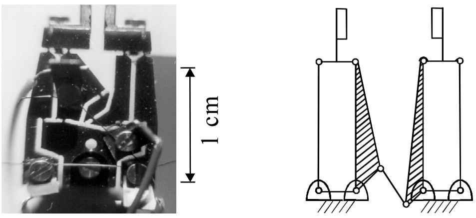
a) b)

Fig.3 An example of mechanical microgripper: a) the prototype, [3]; b) simplified kinematic model.



a) b)

Fig.4 An example of mechanical microgripper: a) the prototype, [4]; b) simplified kinematic model.



a) b)

Fig.5 An example of mechanical microgripper: a) the prototype, [5]; b) simplified kinematic model.

A FORMULATION FOR MULTIOBJECTIVE OPTIMUM DESIGN OF A MICROGRASPING MECHANISM

The first task in design is the choice of mechanical structure for gripping mechanism that satisfies its principal function such as the desired motion of fingers. Then, an optimum design can be formulated as an optimization problem with a multi-objective function that takes into account different performance criteria in the form

$$\min \mathbf{f}(\mathbf{X}) \qquad (1)$$

subjected to

$$\mathbf{g}(\mathbf{X}) < 0\ ;\ \mathbf{h}(\mathbf{X}) < 0 \qquad (2)$$

where **X** is the vector of design variables; each component of the objective function is an expression of a design optimum criterion; each component g_k (k=1,…,m) describes an inequality design constraint; and each component h_l (l=1,…, n) describes en equality design constraint. Constraints can be formulated through the functions **g** and **h** to express design requirements but also limitations for the design variables and objective functions.

There are several alternative methods to solve numerically a multi-objective optimization problem of Eqs. (1) and (2), [6]. Nevertheless, the multi-objective problem can be conveniently solved by using a scalar objective function F(**X**) and standard constrained optimization methods when the number of objective components is limited.

Some main aspects that should be taken into account in the optimum design of microgripping mechanism are the mechanical efficiency, stiffness and adhesive force characteristics.

Maximizing the mechanical efficiency of the mechanism means that a suitable grasping force can be achieved with smaller actuators. However, also the direction of the grasping force should be considered. These two aspects can be taken into account as proposed for example in [7] by using a Grasping Index (GI) in the form

$$GI = \frac{F\cos\psi}{P} \qquad (3)$$

A good practice is also to minimize the variations of the GI in the working range, [7].

Stiffness characteristics of a microgripper are strongly related with the energy needed for the operation. Therefore, minimizing the stiffness can increment the expected performances in terms of grasping forces. Also in this case, it is convenient to avoid big changes in the stiffness performances within the working range.

The adhesive forces are a critical aspect in the operation of microgrippers. According with the application, it could be convenient to maximize the adhesive forces in order to achieve a stable grasp with less grasping force. It could be also convenient to minimize the adhesive forces in order to make easier the releasing of the object.

The above-mentioned aspects are some of the main aspects that can be considered in a multi-objective optimization problem by using proper objective functions. These objective functions can be considered in a scalar function F of the vector function **f** (**X**) introduced in Eq. (1) in the form

$$\min \mathrm{F}(\mathbf{f}(\mathbf{X})) = \min\left(\max\left(\mathrm{f}_1(\mathbf{X}),\ldots,\mathrm{f}_n(\mathbf{X})\right)\right) \qquad (4)$$

Function F (**X**) of Eq.(4) can be subject to design constraints such as

$$\mathrm{a}_\mathrm{m} \le \mathrm{a}_\mathrm{k} \le \mathrm{a}_\mathrm{M} \qquad (5)$$

when a_k is a dimensional design parameter that is limited within practical values.

AN OPTIMUM DESIGN PROCEDURE

It has been chosen to optimize the design of a microgripper having the kinematic chain of Fig. 6. It is composed of two symmetric mechanisms actuated by central link of the parallelograms.

The above-mentioned mechanism has advantageous properties in term of force transmission. It gives also a parallel motion of the fingers. Moreover, the proposed kinematic chain enables to remove the actuator from the area between fingers. Therefore, this microgripper could be suitable as scissor in microsurgery.

It is worth noting that in the following it has been assumed to use POM (Polyoxymethylen) as material for the manufacturing and SMA (Shape Memory Alloy) wires as actuators.

The vector of design parameters $\mathbf{X}=[p_1, ..., p_i, ..., p_n]$ to be optimised can be defined as

$$\mathbf{X} = \left[l, l_3, \alpha_{neutr}, \alpha_{range}, \alpha_{3,neutr}\right] \qquad (6)$$

where l and l_3 are link lengths, α_{neutr} and $\alpha_{3,neutr}$ are rotation angles of links in neutral position and the angle α_{range} is the range of motion of α angles.

Lower and upper bounds for each optimized parameter are determined such as

$$p_{i,lower} \le p_i \le p_{i,upper} \qquad (7)$$

These bounds limit the total size of the mechanism.

In order to obtain the expression of an objective function $f_1(\mathbf{X})$, that takes into account the grasping index, the principle of virtual works is applied and kinematic analysis of the gripping mechanism is used. Because of parallel contact areas of fingers the formulation for the grasping index is

$$\mathrm{GI} = 0.5\cdot\left(\mathrm{tg}\,\alpha - \mathrm{tg}\left(\alpha_3 - 180\right)\right) \qquad (8)$$

Then the objective function $f_1(\mathbf{X})$ can be expressed

$$\mathrm{f}_1(\mathbf{X}) = \frac{GI_{max} - GI_{min}}{GI_{med}} \qquad (9)$$

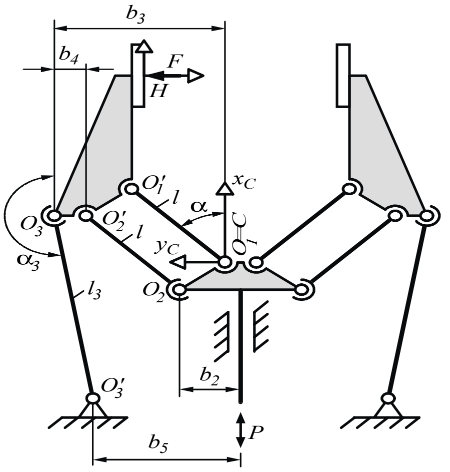


Fig. 6 Kinematic chain of the microgripper with parallel motion of fingers.

where min, max and med indicate minimum, maximum and average of the grasping index within the range of motion of the mechanism.

The goal of the optimization design is to minimize the multi-objective function. Obviously, the minimum possible value of the function $f_1(\mathbf{X})$ is zero. However, $f_1(\mathbf{X})=0$ does not correspond in general to any practical solution since it implies an infinite force transmission factor. Therefore, the grasping index must keep in the range $[GI_{lower}, GI_{upper}]$.

The second objective function $f_2(\mathbf{X})$ is based on the mechanical compliance of the mechanism. The task is to express the directional compliance of the mechanism with respect to the direction of the driving force P. Maximum compliance of half part of the mechanism shown in Fig. 6 satisfies the criterion for optimum design due to the symmetry.

Deflections and internal load of the joint are related

$$\boldsymbol{d}_i = \boldsymbol{C}_{joint}\cdot\boldsymbol{F}_i \qquad (10)$$

where $\boldsymbol{C}_{joint}$ is the 3x3 compliance matrix for the joint.

Principal parts of the mechanism are links with two flexural joints. The deflections of a link can be expressed with respect to the local references $O_i(x_i, y_i, z_i)$. Then, one can express the compliance coefficients $c_{C(i)}$ of particular links that coincides to x_C-direction.

The flexural characteristics of the parallelogram can be computed as

$$\mathrm{s}_\mathrm{par} = \left(\mathrm{c}_{\mathrm{C}(1)}\right)^{-1} + \left(\mathrm{c}_{\mathrm{C}(2)}\right)^{-1} \qquad (11)$$

Therefore, the compliance of half part of the mechanism in direction of driving force P is

$$\mathrm{c}_\mathrm{half} = \left(\mathrm{s}_\mathrm{par}\right)^{-1} + \mathrm{c}_{\mathrm{C}(3)} \qquad (12)$$

Finally, the objective function $f_2(\mathbf{X})$ can be formulated as

$$f_2(\mathbf{X}) = (c_{\text{half}})^{-1} \geq f_{2,\text{des}} \qquad (13)$$

where the value $f_{2,\text{des}}$ is the desired dynamic performance of the mechanism in terms of frequency characteristics.

The third objective function $f_3(\mathbf{X})$ takes into account the adhesive forces. As pointed out in [8] one can write

$$f_3(\mathbf{X}) = F_a = F_W + F_e + F_{ad} = \mu_a F \qquad (14)$$

where F_a is the total adhesive force experienced in a micrograsping, F_W is the Van der Waals force, F_e is the electrostatic force, F_{ad} is the adhesive force due to mechanical actions, F is the grasping force exerted by fingers and μ_a is a global coefficient that depends on the characteristics of the micrograsping and grasped object and can be written as

$$\mu_a = \mu_0 L + \mu$$

The global coefficient μ_a can be expressed as function of L by assuming a coefficient μ_0, which takes into account all other functionalities. The coefficient μ is the conventional friction coefficient.

Once the objective functions has been formulated the inequality constraints ***g*** can be listed as

$$d_f \geq d_{f,min} \qquad (15)$$

$$\alpha_3 - 180 \leq \alpha - 5 \qquad (16)$$

$$x_H \geq x_{H,min} \qquad (17)$$

$$\alpha_{range} \leq \psi_{i,max} \qquad (18)$$

$$\alpha_{3,max} - \alpha_{3,min} \leq \alpha_{range} \qquad (19)$$

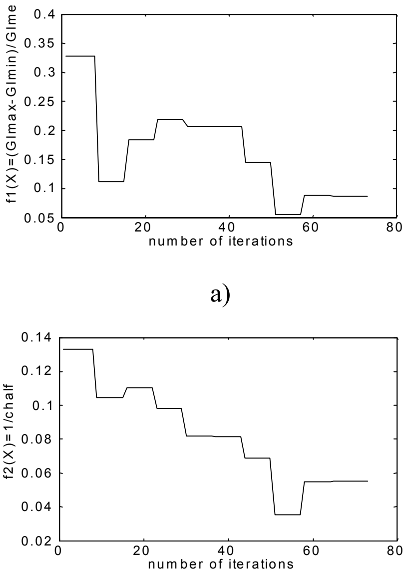
Equation (15) is set to avoid collision of links 2 and 3. For this reason, minimum difference $d_{f,min}$ of the link 3 from the joint O_2 has been assumed. Equation (16) ensures that the links 2 and 3 do not become parallel. In fact, when links 2 and 3 are parallel the mechanism is in a singular position. Equation (17) gives limit of displacement of the finger and equation (18) implies that range of motion of the parallelogram links must be limited by maximum rotation angle of the flexural joint. Equation (19) indicates that range of motion of the link 3 should be smaller than the parallelogram range of motion in order to minimize deformation energy needed for moving the mechanism.

A NUMERICAL EXAMPLE

The proposed method has been implemented in Matlab environment by using Matlab Optimization Toolbox. In particular, *fminimax* has been chosen for the optimization. Table 2 shows the initial and final optimized values of the design variables.

Figures 7 to 9 show the results of the numerical example for the proposed optimum design. The numerical example has been computed assuming $0{,}5 \leq GI \leq 2$; $d_{f,min} = 1$mm; $x_{H,min} = 0{,}5$mm. The size of the object has been assumed L = 10mm. For this size the adhesive forces can be considered as negligible. Therefore, the mechanism has not been optimized from adhesive forces point of view. In particular, Figure 7 shows the Grasping Index GI and the compliance versus the number of iterations giving the optimum solution after 57 iterations. The evolution gives a practical solution for the microgripping mechanism. Figure 8 shows evolution of the formulated constraints to satisfactory agreements. In particular, minimal prescribed displacement of the fingers and maximal range of motion of the link 3 have been met rigorously. The GI is computed with a suitable value within the prescribed range. The collision of the links 2 and 3 and the singular position of the mechanism have been avoided.

Figure 9 shows the evolution of the design parameters. In particular, the optimum design gives the parameters shown in Tab. 2. Figure 10 shows a novel compact microgripper design based on the results of the proposed optimization.



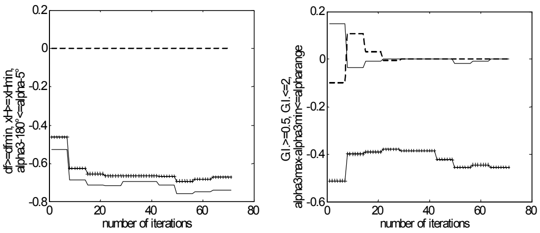
a)

b)

Fig.7 Evolution of the objective functions versus the number of iterations: a) variation of Grasping Index (GI); b) variation of compliance.

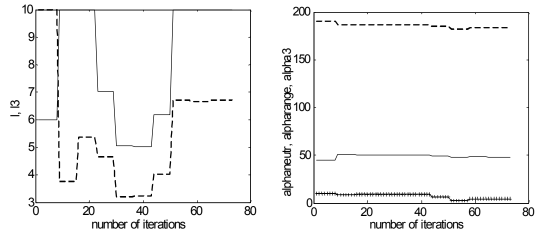
Table 2: Initial parameters and parameters after optimization procedure

	$f_1(\mathbf{X})$	$f_2(\mathbf{X})$	l	l_3	α_{neutr}	α_{range}	α_3	GI
Initial	0.33	0.13	6	10	45	10	190	0.41
Final	0.09	0.06	10	6.7	47.9	4.3	184	0.52



a) b)

Fig.8 Evolution of the constraints versus the number of iterations (lengths are expressed in m and angles in rad): a) $d_f \geq d_{f,min}$ (continuous line); $\alpha_3 - 180 \leq \alpha - 5$ (plus sign line); $x_H \geq x_{H,max}$ (dashed line); b) $GI \geq 0,5$ (continuous line); $GI \leq 2$ (plus sign line); $\alpha_{3,max} - \alpha_{3,min} \leq \alpha_{range}$ (dashed line).



a) b)

Fig.9 Evolution of the design variables versus the number of iterations: a) (link lengths are expressed in mm and angles in deg) l (continuous line); l_3 (dashed line); b) α_{neutr} (continuous line); α_{range} (plus sign line); α_3 (dashed line).

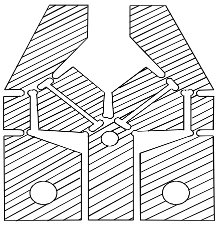


Fig.10 A novel compact microgripper design by using the results of the proposed optimization.

CONCLUSION

In this paper we have proposed a design procedure for microgripping mechanisms as based on an optimization problem that has been formulated by using basic characteristics of the micrograsping and microgripping mechanisms. A novel microgripper has been successfully designed by using the proposed concepts in order to prove the soundness of the proposed numerical design procedure.

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