U.P.B. Sci. Bull., Series D, Vol. 73, Iss. 1, 2011 ISSN 1454-2358

OPTIMUM DESIGN OF SELF CENTERING GRIPPERS

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Scopul sintezei cinematice a mecanismelor este determinarea dimensiunilor elementelor componente, în condițiile impuse prin mişcările unor puncte sau elemente. Rezolvarea unei astfel de probleme se reduce la rezolvarea unui sistem de ecuații neliniare. Ca urnare, problemele de sinteză cinematică nu au soluții unice. Pentru oprimizarea dimensiunilor unui mecanism de prehensiune, funcția obiectiv poate exprima precizia de poziționare a piesei de lucru, mărimea forței motoare, domeniul de fixare stabilă a pieselor etc. In lucrare sunt prezentate unele considerații asupra sintezei optimale a mecanismelor de prehensiune simetrice cu două degete.

The goal of the kinematics synthesis of the linkages is to establish the kinematics dimensions of the component elements provided that some conditions are imposed regarding movements of some points or elements. The resolution of the kinematics synthesis problems is reduced to the resolution of some nonlinear equation systems. As a result, the problems of the kinematics synthesis of linkages do not have unique solutions. In the optimum synthesis of the gripper mechanisms, the objective function may express the positioning precision of the work pieces, the magnitude of the driving force, the domain of the stable fastening of the work pieces etc. In this work, some considerations about the optimum synthesis of the two fingered self centering grippers are shown.

Key words: self centering grippers, optimum design of grippers

Nomenclature

AB, BC, CD, … are the lengths of links (**1**), (**2**), (**3**) …;

φ_{ki} is the angle of the link (k), $k = \overline{1,3}$, in the position i of the gripper;

α is the angle between vectors $\overline{BC}$ and $\overline{PE}$;

Φ_{2i} $i = \overline{1,7}$ are the angles which define the work field of gripper;

ψ_i is the angle between the symmetry axis OX and vector $\overline{PE}$;

F_1, F_2 are the components of clamping force.

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1. Introduction

Many engineering design problems involve multiple objectives and often they are attempted to be solved by converting them into a single complex objective. Moreover, to be able to use the classical optimization method, often such problem are divided into suitable subproblems and solved in stages. The selection of an objective function is one of the most important decisions in the whole optimum synthesis process. In some situations, an obvious objective function exists. In other cases, an objective function exists because the design is part of a larger and complicated system whose end use, is considered to be the best satisfied by having parts which are optimized with respect to certain characteristics [1], [2].

The problem of design of the gripper mechanisms is difficult to optimize because of geometric constraints which make only a tiny fraction of the search space feasible. Grasp force optimization techniques are discussed by Bicchi [3] and Yu et al. [4]. The work presents a mathematical model of the optimum design of the self centering grippers, with two symmetrical fingers and plane active surfaces of the jaws.

A large category of the self centering grippers has the symmetrical structure with respect to a plane which contains the cylindrical work piece axis [1], [5]. The fingers are attached to the connecting rods of the plane linkages. The term *fingers* is used as a generic term to represent any link, finger, effector or fixture in point contact with the work piece being grasped. To the common constructions of grippers, the finger mechanisms are four-bars ones, and the active surfaces of the jaws are plane. The self centering condition is accomplished if the bisector plane of the dihedral angle formed by the plane active surfaces of the jaws passes through a fixed straight line *P* comprised into the symmetry plane of the gripper. This straight line is the cylindrical work piece axis and is perpendicular to the gripper mechanism plane.

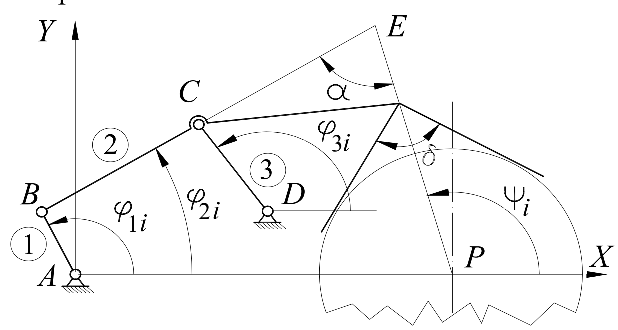

Fig. 1 Self centering gripper

Because the number of the unknown geometric dimensions of the finger mechanisms is finite and relatively small, the self centering condition is realized for a finite number of the diameters of the cylindrical work pieces only. But, from continuity reasons, the position errors of the work piece axes with intermediate diameters are negligible.

The more complicated is the leg structure, the larger is the number of the unknowns of the design problem, and the positioning of the work piece is more accurate.

But, at the same time with the increase of the number of the synthesis equations, the solving precision of these equations decrease. As a result, the previous statement is not entirely true. Moreover, the large pressure angles can appear during working of the gripper, leading to the inadequate force distribution, with unfavorable effects on the working.

In the following, only the four links finger mechanisms are analyzed. The connection kinematic chains [6] are taken into consideration in the kinetostatic analysis only.

The following assumptions are accepted about the kinematic synthesis of the leg mechanisms:

- the links are rigid and the pairs are ideals, without clearance;
- the axes of the rotational joins are perpendicular to the mechanism plane, and the characteristic straight line of the prismatic pairs are comprised in the mechanism plane;
- the links of the fingers mechanisms have symmetrical motions.

2. The kinematic synthesis of the finger mechanisms

The finger mechanism shown in fig. 1 has four links connected by rotational pairs only. The fingers have plane parallel motions and plane active surfaces. *P* is the crossing point between the axis of the cylindrical work piece and the plane of gripper mechanism. The straight line passing through point *P* and intersecting the axis of joint *A* is the abscise *OX* of the fixed system of axes. This can not be the symmetry axis of the gripper. The symmetry axis can be any straight line passing through the *P*. The symmetry axis is chosen in terms of the maximum and minimum values of the angle Ψ between the symmetry axis and the bisecting line *PE*:

$$\psi_{min} = \varphi_{20} + \Phi_{2min} + \alpha,$$

$$\psi_{max} = \varphi_{20} + \Phi_{2max} + \alpha,$$

and in terms of the magnitude of the dihedral angle between the active surfaces of the finger jaw.

The equations of the kinematic synthesis of the finger mechanisms are:

$$AB \cos\varphi_{1i} + BC \cos \varphi_{2i} - CD \cos \varphi_{3i} - X_D = 0;$$

$$AB \sin\varphi_{1i} + BC \sin \varphi_{2i} - CD \sin \varphi_{3i} - Y_D = 0; \quad (1)$$
$$(X_P - X_E) \tan(\varphi_{2i} + \alpha) + Y_E = 0,\ i = \overline{1,\ n},$$

where:

$\varphi_{2i} = \varphi_{20} + \Phi_{2i}$,
$X_E = AB \cos\varphi_{1i} + BE \cos \varphi_{2i}$,
$Y_E = AB \sin\varphi_{1i} + BE \sin \varphi_{2i}$.

The unknowns of the synthesis problem are: the lengths AB, BC, CD, BE, X_D, Y_D, X_P and the angles φ_{20}, α, φ_{1i}, φ_{3i}, $i = \overline{1,\ n}$. It is considered that the values of the angles Φ_{2i}, $i = \overline{1,\ n}$, $\Phi_{2i} \neq \Phi_{2j}$, $i \neq j$, which define the working field of the gripper, are known.

Note that, because the system (1) is homogenous, the trivial solution: $AB = BC = CD = BE = X_D = Y_D = X_P = 0$, is accepted for any values of the position angles. Therefore, the length BC of the connecting rod (**2**) is considered as measure unit for length. From compatibility condition of the equations (1) it results $n = 8$.

The self centering condition is realized exactly only in the positions defined by angles Ψ_i, $i=\overline{1,8}$ i.e. by eight distinct values of the diameters of the cylindrical work pieces.

The work field of the gripper is bordered by the extreme values Ψ_{21} and Ψ_{28} of the angles Ψ_{2i}. For all the rest of diameters, comprised in the work field, the deviations from the prescribed position of the work pieces axes are insignificant. The position errors are owed both to the geometry of gripper, which is defined by a finite number of parameters, and to the numerical procedure errors of the synthesis equations (1).

With values $\Psi_{2i} = 0.0249333(i - 1)$, $i = \overline{1,8}$, the following dimensions of the gripper shown in Fig. 1 have been calculated:
$AB = .94472$, $BC = 1$, $CD = .49896$, $BE = 2.00256$, $X_D = .36543$, $Y_D = .34866$, $X_P = 1.67303$, $\alpha = 1.73995$, $\varphi_{20} =.13995$.

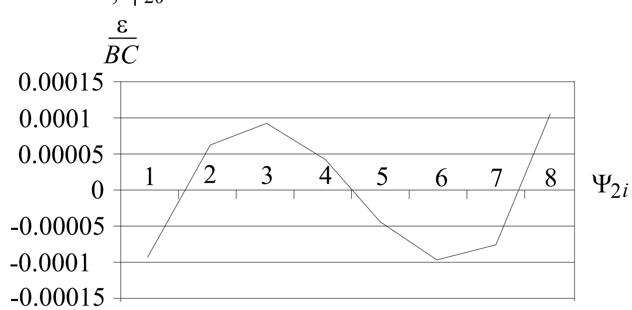

Fig. 2 Positional deviation of cylindrical work pieces which are grasped in gripper with dimensions calculated by kinematic synthesis

Following the analysis of gripper with these dimensions, the position errors of the work pieces axes have been calculated; these errors are displayed in fig. 2.

3. Kinetostatic analysis of the finger mechanism

The goal of the kinetostatic analysis is to establish the reaction force distribution and to compute the magnitude of the driving force [7].

The kinetostatic analysis of the finger mechanism is made in the following assumptions:

- the weight and inertia forces of the gripper components are not take into consideration; this assumption is true because the gripper may be operated in any position with respect to the vertical one;
- the frictional forces from kinematic pairs are ignored;
- the kinematic pairs are ideals, without gaps; all the cylindrical pairs have the axes perpendicular to the gripper plane, and all prismatic pairs have the characteristic straight lines into the gripper plane;
- the mechanisms of the fingers are symmetrical, both from geometrical point of view and the force distribution between links and between finger jaws and work piece.

The two grip forces, namely $\overline{F}_1$ and $\overline{F}_2$, which acted from work piece to the finger jaw (Fig. 3) has the resultant $\overline{F}$, which has as support the straight line *HP* perpendicular to the symmetry axis of the gripper.

In the kinetostatic analysis, the symmetry axis of any gripper crosses the axis of the cylindrical work piece, and coincide with the axis of the translational driving pair [6], [8], [9]. This axis is the abscise *O'X'* of the fixed coordinate system (fig. 4).

The connecting kinematic chain [6] is made up of three links, two binary links and a ternary link, joined by five pairs. The driving pair connected the central link to the frame.

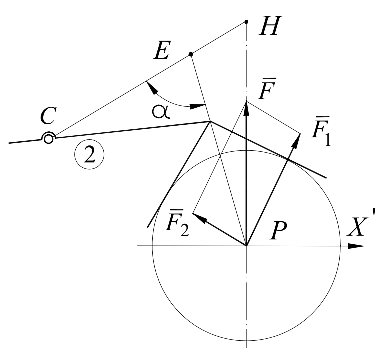

Fig. 3 The grasping forces

The components of the reaction forces with respect to the fixed system of axes $X'O'Y'$ are :

$$R_{03X'} = \frac{D1}{D2}(X'_D - X'_C);$$

$$D2 = Y'_B(X'_D - X'_C) - Y'_C(X'_D - X'_B) + Y'_D(X'_C - X'_B);$$

$$D1 = F_{X'}(Y'_H - Y'_B) + F_{Y'}(X'_B - X'_H);$$

$$R_{03Y'} = \frac{D1}{D2}(Y'_D - Y'_C);$$

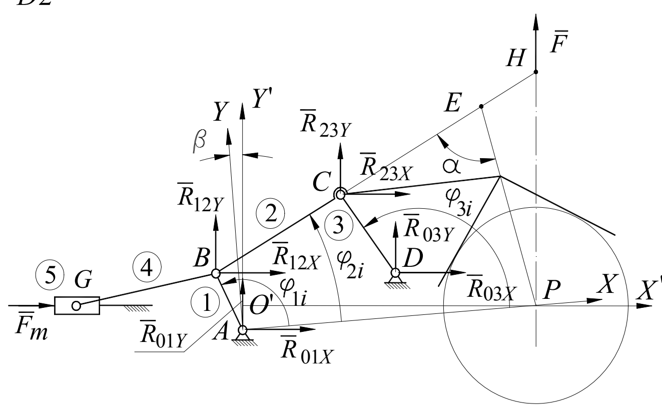

Fig. 4 The reaction forces in pairs of the gripper mechanism

$$R_{12X'} = -F_{X'} - R_{03X'};\ \ R_{12Y'} = -F_{Y'} - R_{03Y'};$$

$$R_{54X'} = \frac{D3}{D4}(X'_G - X'_B);\ R_{54Y'} = \frac{D3}{D4}(Y'_G - Y'_B);$$

$$D3 = R_{12X'}(Y'_A - Y'_B) - R_{12Y'}(X'_A - X'_B);$$

$$D4 = X'_G(Y'_A - Y'_B) + X'_B(Y'_G - Y'_A) + X'_A(Y'_B - Y'_G);$$

$$R_{01X'} = R_{12X'} - R_{54X'};$$

$$R_{01Y'} = R_{12Y'} - R_{54Y'},$$

where:

$$F_{X'} = 0;\ \ F_{Y'} = F.$$

$$X'_B = X'_A + X_B \cos\beta - Y_B \sin\beta;$$

$$Y'_B = Y'_A + X_B \sin\beta + Y_B \cos\beta;$$

$$X'_C = X'_A + X_C \cos\beta - Y_C \sin\beta;$$

$$Y'_C = Y'_A + X_C \sin\beta + Y_C \cos\beta;$$

$$X'_D = X'_A + X_D \cos\beta - Y_D \sin\beta;$$

$Y'_D = Y'_A + X_D \sin\beta + Y_D \cos\beta;$
$X'_E = X'_A + X_E \cos\beta - Y_E \sin\beta;$
$Y'_E = Y'_A + X_E \sin\beta + Y_E \cos\beta;$
$X'_G = X'_A + X_G \cos\beta - Y_G \sin\beta;$
$Y'_G = Y'_A + X_G \sin\beta + Y_G \cos\beta;$
$X'_H = X'_P;$
$Y'_H = Y'_B + (X'_P - X'_B)\tan(\varphi_2 - \beta),$
$X'_A = X_P(1 - \cos\beta);$
$Y'_A = -X_P \sin\beta.$

The angle between the positive *O'X'* axis and the positive *OX* axis is denoted by β. All angles are taken as positive if measured counterclockwise.

The magnitude of the driving force is: $F_m = 2R_{54X'}$.

The ordinate Y'_A of the pair center *A* and the coordinates (X'_D, Y'_D) of the center of the pair *D*, with respect to the fixed system, of axes are calculated in terms of the magnitude of the angle β. This angle is chosen as function of the magnitude of the gripper work field and the maximum driving force.

4. Optimum synthesis of the grippers

The kinematic dimensions of the finger links are calculated as solution of a nonlinear equation system. Because these systems do not have unique solutions, it is necessary to choose the best solution from a certain point of view. This is realized by minimizing an objective function which expresses the mathematical model of one or more characteristics of the gripper. These characteristics can be:

- the maximum deviation of the cylindrical work piece axis position with respect to the imposed value, i.e. the positioning precision of the work pieces,
- the magnitude of the driving force, required for fastening of the work piece,
- the domain of the stable fastening of the work pieces, etc.

The objective function depends on the kinematic dimensions (linear and angular) of the finger links, and is minimized in the presence of the some constrains, equality type and inequality type [10], [11].

The inequality type constrains limit:

- the domain in that the contact generatrices between jaws and cylindrical work piece can be found;
- the magnitudes of the reaction forces between fingers and work piece, witch must be nonnegative;

- the magnitude of the pressure angles.

The equality type constrains are made up by equalizing with zero of the position transmission functions; these are the equations of the kinematic synthesis of the finger mechanisms.

5. Example

In order to exemplify and verify the proposed synthesis method, a numerical example has been solved. The kinematic dimensions links of the gripper shown in Fig. 1, obtained after solving the system (1) are:

The work field is defined by $\Phi_{2i} = 0.0249333(i-1)$, $i = \overline{1,8}$.

One of the optimum solutions of the gripper schematized in Fig. 1 is obtained by minimizing the following objective function:

$F_O = \max\{F_{mi}, i = \overline{1,8}\}$, where

$F_{mi} = 2R_{54X_i'}$, $F_X = 0$; $F_Y = F = 1$.

The constrains take into consideration are:

$g_1 = AB\cos\varphi_{1i} + BC\cos\varphi_{2i} - CD\cos\varphi_{3i} - X_D = 0$;

$g_2 = AB\sin\varphi_{1i} + BC\sin\varphi_{2i} - CD\sin\varphi_{3i} - Y_D = 0$;

$g_3 = (X_P - X_E)\tan(\varphi_{2i} + \alpha) + Y_E = 0$, $i = \overline{1,8}$,

$g_4 = \psi_{max} + 0.5\delta - \pi < 0$;

$g_5 = \psi_{max} - 0.5\delta - 0.5\pi < 0$;

$g_6 = \psi_{min} + 0.5\delta - 0.5\pi > 0$;

$g_7 = \psi_{min} - 0.5\delta > 0$.

where: $\psi_{max} = \varphi_{20} + \Phi_{2\max} + \alpha$;

$\psi_{min} = \varphi_{20} + \Phi_{2\min} + \alpha$.

The solutions of the optimum problem are:

$AB = 1.11083$, $BC = 1$, $CD = 0.62873$, $X_D = 0.35124$, $Y_D = 0.28289$,
$BE = 1.78802$, $\alpha = 1.96565$, $X_P = 1.53405$, $\beta = 0.06381$, $BG = 1.10599$.

For comparison, in Fig. 7 is displayed the diagram of the driving force in gripper with dimensions calculated by kinematic synthesis, i.e. by solving the equations (1).

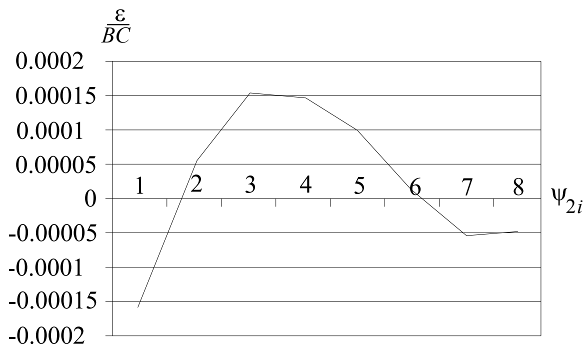

Fig. 5 Positional deviation of axes of cylindrical work pieces which are grasped in gripper with dimensions calculated by optimum synthesis

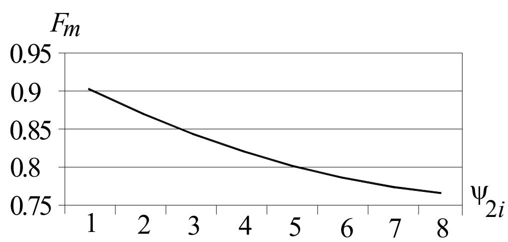

Fig. 6 Diagram of driving force for gripper with dimensions calculated by solving of optimization problem

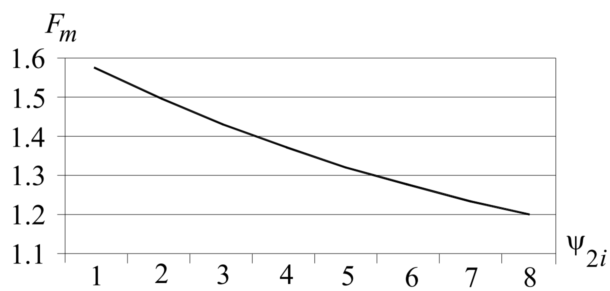

Fig. 7 Diagram of driving force for gripper with dimensions calculated by solving of kinematic synthesis problem

6. Conclusions

The problem of design of the gripper mechanisms is the nonlinear programming one. The objective function expresses one of a following characteristics:

- the magnitude of the driving force,
- the maximum deviation of the work piece axis position with respect to the imposed value,
- the stable fastening field of the work pieces etc.

The unknowns of this problem are the kinematic dimensions of the links and the constrains are the equations of the kinematic synthesis of the finger mechanism.

The comparative analysis of two gripper mechanisms among which the second is designed by the proposed method is conclusive.

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