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OPTIMAL SYNTHESIS OF THE MANIPULATOR USING TWO COMPETITIVE METHODS

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Abstract. *This paper defines a program realization for finding the optimal geometry of a planar Z-mechanism. The paper shows the mathematical procedure for defining the objective function, the constraint function and the search fields which are used for solving the optimization problem. Starting from the solutions in practice, a numerical example is given to determine an optimum design with four optimization parameters. All the optimization parameters are geometric on the mechanism for defining the bucket position. The problem is solved by two different numerical methods - the method of formal search of hyperspace (passive scanning method) and the approximate method of Sequential Quadratic Programming - SQP (applying the function fminmax of the Matlab optimization toolbox). The verification is performed with animation using software for geometric modeling. The results are graphically illustrated.*

Key Words: *Mining Machine, Wheel Loader Z – Mechanism, Passive Scanning, Optimum Design of Mechanism, Numerical Realization, SQP*

1. INTRODUCTION

For working with bulk material the wheel loaders have a mechanism that enables the position adjustment - an inclination angle of the bucket. At lifting, the bucket should keep an upward position without changing the inclination. This can be achieved by adjusting the geometry of the parts of the bucket movement mechanism. One of the mechanisms providing for it is known as the Z - mechanism (Fig. 1). The task of finding a solution for the special mechanism providing for a special request is known as the optimal synthesis according to the Theory of Mechanisms.

Solving this problem is a common example of research and development. The similarity of different plane mechanisms of the machines offers the possibility of using the same optimization procedure. Nowadays there is a variety of mathematical methods

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in use, from the classical one, based on the authorized procedures of differential programming, gradient methods, the method of polyhedra (Nelder-Mead methods) [1], approximate methods of programming and sequential quadratic programming [2], up to the modern methods based on the techniques of genetic algorithm [3], ACA algorithm (Ant Colony Algorithm) [4] and simulation [5].

This paper first presents the method of formal searching for optimal solutions based on the computer changes of the geometric parameters of the mechanism, followed by the method of Sequential Quadratic Programming. Changing the parameters in the method of formal searching is performed incrementally by taking discrete values of independent parameters in an increasing order (scanning technique) [6], [7].For the evaluation of the effectiveness of the passive formal search method, the method of Sequential Quadratic Programming (SQP) is applied in this paper.

The complexity of the general approach to the problem can be seen in the work by Yang Yu [8] where the optimization is performed with twenty-two parameters. Besides geometric optimization parameters, the synthesis can also introduce the constraints of internal mechanism forces. Such an approach can be found in the work of Gao Xiuhua [9] (derived using the Adams software package), and Rongyi Zhang [10], using the Matlab programming environment with the use of a combination of three optimization algorithms. Because of the complexity of the general approach, this paper deals with the mechanism synthesis based on a small number of optimization parameters.

2. Geometric Model of the Z-Mechanism

A planar mechanism of a manipulator loader consists of an arm (1) with a bucket (4) and a lifting hydraulic actuator (5), Fig. 1. The arm (1) possesses a Mechanism for Defining the Bucket Position (MDBP) that does loading, transport position holding and emptying of the bucket. This mechanism consists of a tilting hydraulic actuator (6), a two-arm lever (2) and a coupling rod (3) (Fig. 1).

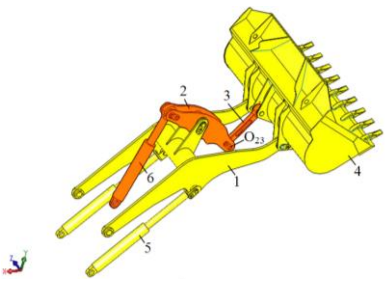

Fig. 1 Geometric model of the Z – mechanism for defining the bucket position (MDBP)

Solving the optimization problem involves finding a geometry of mechanism for defining the bucket position to ensure minimal change in the tilt of the bucket when the arm of the loader is lifting from the minimum to the maximum slope angle β, min {FC}. From there, it is possible to search for optimization parameters in the MDBP mechanism geometry. The mechanism for the lifting arm is designed from the given operating conditions of the bucket position and is not subject to optimization. The optimization parameters can therefore be the position of the bearing of the hydraulic actuator (6), the geometry of the two-arm lever (2) and the length of the coupling rod (3). In this study, four parameters are chosen to optimize the MDBP mechanism related to the position of the bearing of the hydraulic actuator (6) and linkage O_{23} on the lever (2).

For an efficient solution of multidimensional problems with constraints, numerical methods with passive searching can be used [6]. These methods use a fixed interval of indetermination (H), where the field of change of independent variables $\vec{z} = \{z_1, z_2, z_3, z_4\}$ is divided by the selected number of points equal to the number of sub-areas. These points serve as the basis for the construction of n dimensional space. The objective function $FC(\vec{z})$ is calculated at each node of the grid thus formed.With the analysis of all solutions the one that is the most advantageous is chosen. The advantage of the passive search method is in the reliability of searching. A disadvantage of multidimensional problems of passive searching lies in the number of calculation procedures. Therefore, this paper employs the procedure of choice (constriction) of the field of search based on the testing of the objective function. The testing determines the solution with the good initial values of $FC(\vec{z})$ based on a large interval of indetermination. After identifying the "good areas" of solution, the subject of solution is the grid with a fine interval of indetermination. Such a model with a reduced number of optimization parameters (z_1, z_2, z_3, z_4) and numerical implementation can give sub-optimal solutions thanks to the simplicity of the algorithm search. The synthesis procedure for an MDBP mechanism is illustrated in Fig. 1.

3. Mathematical Formulation of the Problem

The formation of a mathematical model for optimization according to Fig. 1 includes defining a planar geometric model of the manipulator. The manipulator is a planar (2D) mechanism with an arm for carrying the bucket and a mechanism for defining the bucket position. A mechanism for defining the bucket position is labeled with darker shades in Fig. 1. The whole mathematical model uses the global Cartesian x-y coordinate system and local coordinate systems of the parts of the mechanism shown in Fig. 2. Fig. 2 shows four parts of the mechanism. The planar form of geometry of these two coupled mechanisms with the selected marked positions of parts is given in Fig. 3.

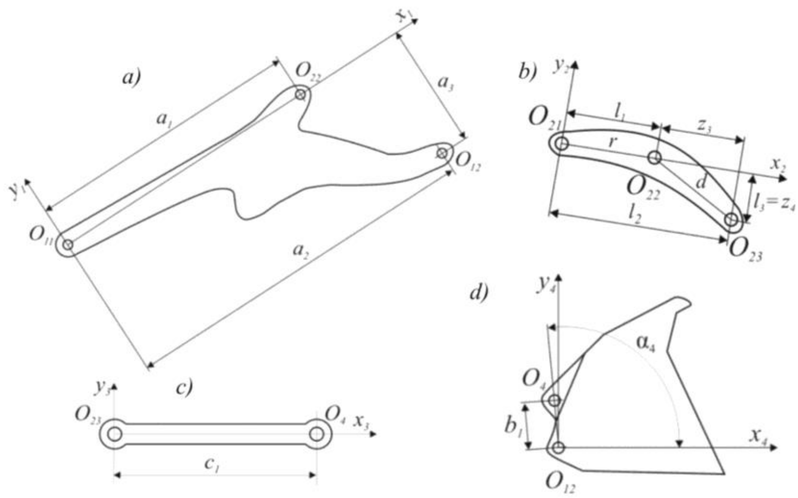

Fig. 2 Parts of MDBP: a) the arm of the manipulator, b) the two-arm lever, c) the coupling rod, d) the bucket

Let us define the geometry of the rigid mechanical system in Fig. 1:The coordinates of linkage O_{11} are given values X_{11}, Y_{11} of some type of a loader. The coordinates of linkage O_{12} at the top of the arm are computed as:

$$X_{12} = X_{11} + a_2 \cdot \cos\beta + a_3 \cdot \cos(90-\beta) \tag{1}$$

$$Y_{12} = Y_{11} + a_2 \cdot \sin\beta - a_3 \cos\beta \tag{2}$$

The coordinates of bearings of the two-arm lever, the position of linkage O_{22} are computed as:

$$X_{22} = X_{11} + a_1 \cdot \cos\beta \tag{3}$$

$$Y_{22} = Y_{11} + a_1 \cdot \sin\beta \tag{4}$$

The coordinates of linkage O_{21} are determined by an intersection of the two circles with the center in linkage O_6 whose radius is c_6 – the length of the hydraulic actuator (6) and the circle with the center in linkage O_{22} whose radius is equal to the length of the arm l_1 of the lever (2). We consider that the length of the hydraulic actuator (6) is constant. The coordinates of linkage O_{21} are obtained by solving the equation:

$$\begin{aligned} (X_{21} - X_{22})^2 + (Y_{21} - Y_{22})^2 &= l_1^2 \\ (X_{21} - X_6)^2 + (Y_{21} - Y_6)^2 &= c_6^2 \end{aligned} \tag{5}$$

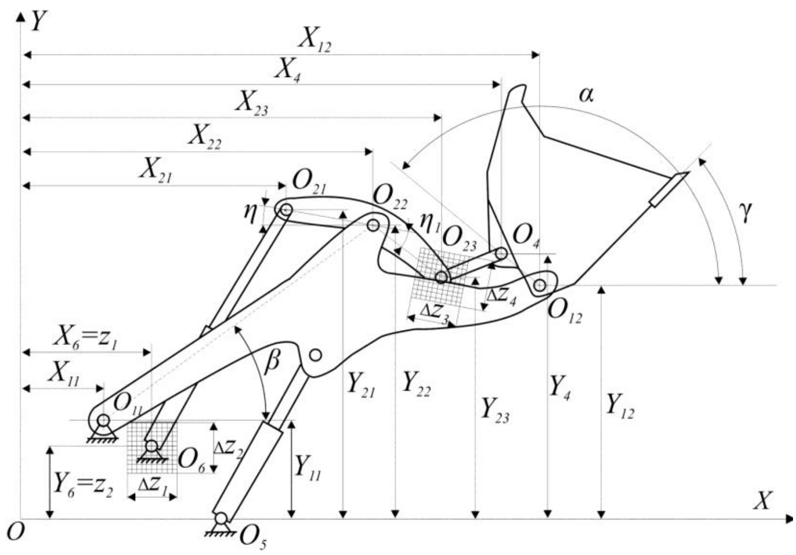

Fig. 3 Geometric model of the manipulator of the loader

The distance between the centers of the circles is computed as:

$$D = \sqrt{(X_6 - X_{22})^2 + (Y_6 - Y_{22})^2} \tag{6}$$

Value F and the coordinates of linkage O_{21} are computed as:

$$F=\frac{1}{4}\sqrt{(D+l_1+c_6)\cdot(D+l_1-c_6)\cdot(D-l_1+c_6)\cdot(l_1-D+c_6)} \tag{7}$$

$$X_{21(1,2)}=\frac{X_{22}+X_6}{2}+\frac{(X_6-X_{22})\cdot(l_1^2-c_6^2)}{2\cdot D^2}\pm 2\frac{Y_{22}-Y_6}{D^2}F \tag{8}$$

$$Y_{21(1,2)}=\frac{Y_{22}+Y_6}{2}+\frac{(Y_6-Y_{22})\cdot(l_1^2-c_6^2)}{2\cdot D^2}\mp 2\frac{X_{22}-X_6}{D^2}F \tag{9}$$

Let us determine the coordinates of linkage O_{23}. Angle η_1 between direction r and d of the two-arm lever is computed as:

$$\eta_1=arctg\frac{l_3}{l_2-l_1} \tag{10}$$

Variable angle η (between the arm and the two-arm lever), if is $X_{22}-X_{21}>0$ is then computed as:

$$\eta=arctg\frac{Y_{21}-Y_{22}}{X_{22}-X_{21}} \tag{11}$$

If $X_{22}-X_{21}=0$, angle $\eta=90°$, and if $X_{22}-X_{21}<0$, angle η is computed as:

$$\eta=180^\circ-arctg\frac{Y_{21}-Y_{22}}{X_{21}-X_{22}} \tag{12}$$

Length d of the arm of the two-arm lever (Fig. 2b) is computed as:

$$d=\sqrt{(l_2-l_1)^2+l_3^2} \tag{13}$$

Coordinates of linkage O_{22}, are computed as:

$$X_{23}=X_{22}+d\ \cos(\eta+\eta_1) \tag{14}$$

$$Y_{23}=Y_{22}-d\ \sin(\eta+\eta_1) \tag{15}$$

The introduced optimization parameters z_1, z_2, z_3, z_4 correspond to the required geometry of the Z - mechanism by the following relations:

$$z_1=X_6 \tag{16}$$

$$z_2=Y_6 \tag{17}$$

$$z_3=l_2-l_1 \tag{18}$$

$$z_4=l_3 \tag{19}$$

The coordinates of linkage O_4 (X_4, Y_4) are determined using the intersection of the circle with the center of linkage O_{23} whose$_1$. The solution of coordinates X_4, Y_4 is obtained from the equation: radius is the length of coupling rod c_1 and the circle with the center of linkage O_{12} whose radius is length b:

$$\begin{aligned}(X_4 - X_{23})^2 + (Y_4 - Y_{23})^2 &= c_1^2 \\ (X_4 - X_{12})^2 + (Y_4 - Y_{12})^2 &= b_1^2\end{aligned} \tag{20}$$

The distance between the centers of the circles and value F_1 are computed as:

$$D_1 = \sqrt{(X_{12} - X_{23})^2 + (Y_{23} - Y_{12})^2} \tag{21}$$

$$F_1 = \frac{1}{4}\sqrt{(D_1 + c_1 + b_1)\cdot(D_1 + c_1 - b_1)\cdot(D_1 - c_1 + b_1)\cdot(c_1 - D + b_1)} \tag{22}$$

Coordinates of linkage O_4:

$$X_{4(1,2)} = \frac{X_{12} + X_{23}}{2} + \frac{(X_{12} - X_{23})\cdot(c_1^2 - b_1^2)}{2\cdot D_1^2} \pm 2\frac{Y_{23} - Y_{12}}{D_1^2}F_1 \tag{23}$$

$$Y_{4(1,2)} = \frac{Y_{23} + Y_{12}}{2} + \frac{(Y_{12} - Y_{23})\cdot(c_1^2 - b_1^2)}{2\cdot D_1^2} \mp 2\frac{X_{23} - X_{12}}{D_1^2}F_1 \tag{24}$$

Bucket tilt angle for the current value of arm slope β is computed as:

$$\alpha(\beta) = arctg\,\frac{Y_4 - Y_{12}}{X_4 - X_{12}} \tag{25}$$

The back angle of bucket γ is determined by the position of the angle of bucket α and constant α_4 (Fig. 2d):

$$\gamma = \alpha - \alpha_4 \tag{26}$$

The objective function is the minimum change in the slope of the bucket while the arm of the loader is lifting:

$$FC(z_1, z_2, z_3, z_4) = \alpha_{\max} - \alpha_{\min} \tag{27}$$

The constraint functions are determined by inequalities:

$$\begin{aligned}G_1 &= z_1 - A > 0 \qquad G_5 = z_3 - E > 0 \\ G_2 &= z_1 - B < 0 \qquad G_6 = z_3 - F < 0 \\ G_3 &= z_2 - C > 0 \qquad G_7 = z_4 - U > 0 \\ G_4 &= z_2 - D < 0 \qquad G_8 = z_4 - H < 0\end{aligned} \tag{28}$$

where: A, B, C, D, E, F, U, H – are the constants of the search space.

4. ALGORITHM AND PROGRAM

Fig. 4 presents the algorithm of global numerical procedures developed for the solution of the optimal mechanism synthesis. The algorithm shows that the scanning method is realized by an increment change of the optimization parameters in a permissible four-dimensional hyperspace. The permissible hyperspace is empirically determined. The initial setting of geometry of both mechanisms is provided through the files DAT1-DAT6. The solutions of objective function FC for discrete values of independent parameters $z_1 \div z_4$ are entered in the file DAT7. By comparing these solutions, the solution that is characterized by the minimum value of objective function FC is chosen. Then the obtained solution is checked from the point of numerical accuracy, satisfying the given nominal characteristics of the reach and lift height. After that, the continuity of coupling of the parts of mechanism for defining the bucket position is also checked. The following numerical example illustrates the application of this mathematical model, the efficiency of the algorithm and the practical realization of optimal synthesis.

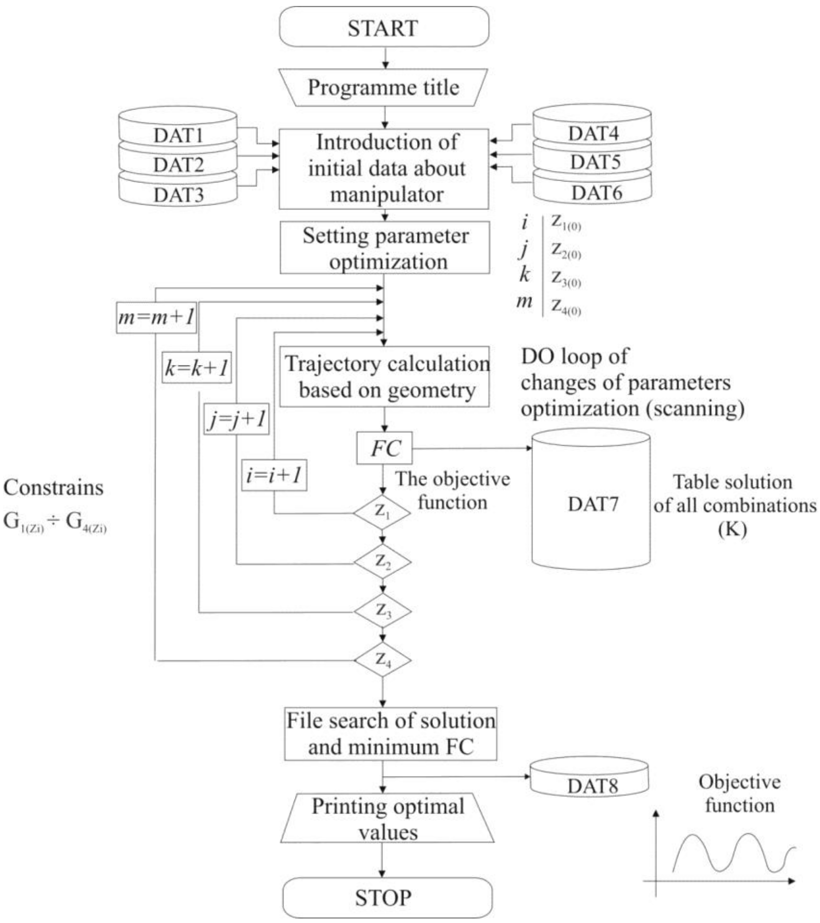

Fig. 4 The algorithm of the program for optimal numerical synthesis of MDBP

5. NUMERICAL EXAMPLE

The aim of this study is to search for the design of the mechanism for defining the bucket position which minimizes the angle of the bucket tilt during the bucket lifting operation. The initial solution is based on freely assumed geometry which is in this case taken from photographs and sketches [11] (Komatsu WA320). Four parameters are selected to optimize the synthesis: x, y coordinates of bearings of the hydraulic mechanism for defining the bucket position and x, y local coordinates of linkage O_{23} of the two-arm lever. The procedure for the algorithm program flow is fast and numerically stable. The stability is based on the simplicity of analytical modeling geometry.

Angle β is the slope angle of the arm in relation to the horizontals and ranging, in this case, from -24^o to 62^o. Parameters z_1, z_2 represent the search field of bearings position O_6, where the geometry is in the following ranges: in the x-axis direction z_{1min}=0.94 m; z_{1max}=1.14 m (Δz_1=0,2 m) (A=0.94 m; B=1.14 m) and in the y-axis direction z_{2min}=1.645 m; z_{2max}=1.845 m (Δz_2=0.2 m) (C=1.645 m; D=1.845 m). The allowable field defined by constants A, B, C, D is chosen on the basis of the available space on the arm. By choosing M = 50 points of change of one independent parameter of optimization, the interval of indetermination is:

$$H_1 = 2\frac{B-A}{M-1} = 2\frac{1,14-0,94}{50-1} = 0,00816 \text{ [m]} \tag{29}$$

Parameters z_3, z_4 represent the search field of the position of linkage O_{23} in the local coordinate system of the two-arm lever, the size of change is in the area: z_{3min}=1.4 m; z_{3max}=1.5 m (Δz_3=0.1 m), (E=1.4 m; F=1.5 m) in the x-axis direction, and z_{4min}=0.175 m; z_{4max}=0.275 m (Δz_4=0.1 m), (U=0.175 m; H=0.275 m) in the y-axis direction. The field is empirically chosen.

Initial zeros are: z_1=1.04 m, z_2=1.745 m, z_3=1.45 m, z_4=0.225 m. These areas of solutions of the optimization task determined the allowable space of search-scanning. The dividing of the permissible field of parameters z_3 and z_4 by the N = 50 points is selected, as well as the dividing of the permissible field of parameters z_1 and z_2 by M = 50 points. In this way a number of combinations of K=M^2•N^2=6250000 are obtained. From the file DAT-8 we can read the optimal parameters of the mechanism for defining the bucket position. Based on these parameters, it is possible to draw curves of objective function FC, depending on the angle of the slope of the arm β for the optimal and initial solution (Fig. 5). Starting from the fixed size of the loader mechanism given in Table 1, the MDBP optimal solutions are obtained, given in Table 2. The curves of the objective function of the required MDBP are plotted for the optimal solution.

Table 1 Initial data of model

a_1 (m)	a_2(m)	a_3 (m)	l_1 (m)	l_2 (m)	l_3 (m)	a_1 (m)	b_1 (m)
1.800	2.550	0.865	0.720	1.450	0.225	0.765	0.370

Table 2 Values of the obtained optimal solution

	Optimal parameters				Objective function
	z_1 (m)	z_2(m)	z_3(m)	z_4(m)	FC (˚)
Initial zeros	1.04	1.745	1.45	0.225	**7.364**
Optimal values	0.973	1.678	1.400	0.175	**1.707**

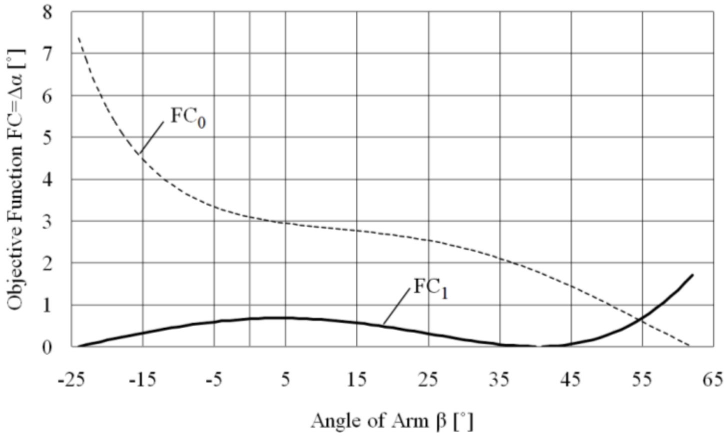

Fig. 5 Curve of initial FC_0 and curve of optimal solution FC_1

The verification is performed by simulation of the working mode (meshing) of the mechanism, in the SolidWorks software, by using the option ***blocks*** which is suitable for the simulation of planar mechanisms. This achieved the verification of the behavior of the mechanism in successive positions, Fig. 6. It provides a functional control study of the mechanism and eliminates errors.

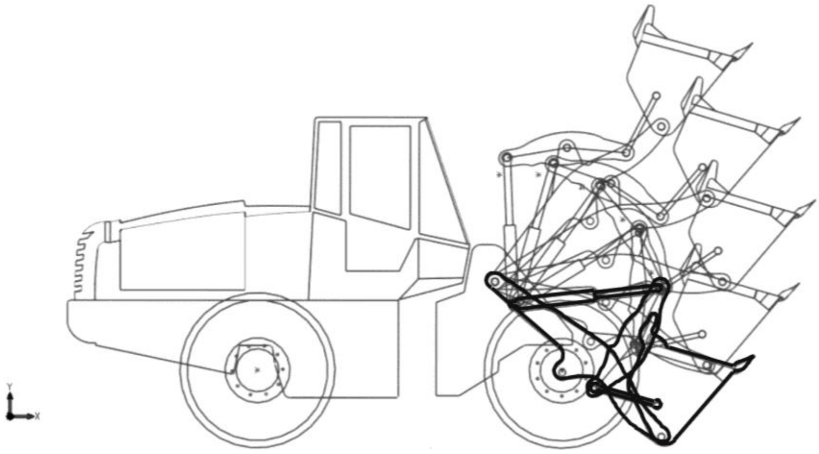

Fig. 6 Simulation of the obtained optimal solution

6. Minimization Using SQP Method

In order to assess the benefits from the chosen method of minimizing the objective function, the method of the Sequential Quadratic Programming (SQP) is used. Minimization is performed by programming the objective function and constraint function in Matlab by using the program function (command) **fminimax** as part of the Matlab optimization toolbox. The general quadratic programming problem is defined as:

$$\min f(z) = c^T z + \frac{1}{2} z^T H \cdot z \tag{30}$$

Where: $A \cdot z \leq b$, $z \geq 0$ (31) are the constraints in the form of inequality,

c – the n-dimensional vector that describes the coefficients of linear terms of the objective function,
z – the n-dimensional vector of unknown values,
H – the (*n*×*n*) symmetric matrix that describes the coefficients of square terms of the objective function,
A – the (*m* × *n*) matrix of constraints, and,
b – the *n*-dimensional vector of constraints [12].

5.1. Function minimax

Function minimax (fminimax) is part of the Optimization Toolbox in Matlab, which finds the minimum of problems determined by the function:

$$\min_z \max_i F_i(z) \text{ such that is } \begin{cases} c(z) \leq 0 \\ ceq(z) = 0 \\ A \cdot z \leq b \\ Aeq \cdot z = beq \\ lb \leq z \leq ub \end{cases} \tag{32}$$

Where the variables on the right side are the constraints:
c(*z*), *ceq*(*z*) – vectors of constraints in the form of inequality and equality,
A – matrix and *b* – vector are, respectively, the coefficients of constraints in the form of linear inequalities,
Aeq – matrix and beq - vector are, respectively, the coefficients of linear constraints in the form of equity,
lb – vector or matrix of lower bounds of constraints,
ub – vector or matrix of upper bounds of constraints.

In the model that is described by equations 1-28, we use only constraints *lb*, *ub* – the vectors of lower and upper bounds of the search field of the optimization parameters solution (*A*, *B*, *C*, *D*, *E*, *F*, *U*, *H*), whose values are listed in the previous numerical example [13].

Based on the function fminimax, where it is necessary to define the objective function and the constraints, the desired optimal parameters are obtained:

```
z = fminimax(fun,z0,A,b,Aeq,beq,lb,ub)
```
(33)

where: *z* – required parameters, *fun* – objective function, z_0 – initial parameters *A*, *b*, *Aeq*, *beq*, *lb*, *ub* – constraints. These values are defined above in equations 1÷28, since in this case constraints *A*, *b*, *Aeq* and *beq* are not used. They are written as an "empty" matrix. The inputs of constraints are in the form of the lower bounds - lb and the upper bounds - ub. In this case, the line of the code of function fminimax looks like:

```
parameters=fminimax('Objectfun',parametri0,[],[],[],[],lb,ub)
```
(34)

SQP has performed the verification of the previous procedure and the optimization achieved by using the passive formal search. The results obtained by the SQP method are shown in the following diagram, Fig. 7, and a table of optimal solutions.

Table 3 Values of obtained optimal solutions by using the function fminimax

	Optimal parameters				Objective function
	z_1 (m)	z_2(m)	z_3(m)	z_4(m)	FC (˚)
Initial zeros	1.04	1.745	1.45	0.225	**7.364**
Optimal solution	1.0176	1.7188	1.4095	0.2002	**0.3518**

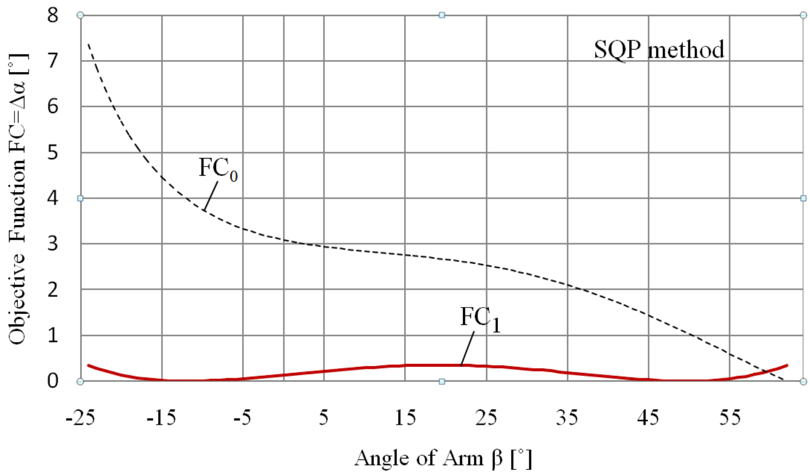

Fig. 7 Curve of initial FC_0 and optimal FC_1solutions, obtained by using the Minimax function

7. Conclusion

1. The mathematical model of optimization operates with four independent parameters out of the potential eight. Even four parameters of optimization give a solution of objective function (change of the tilt is less than two degrees) good enough for practical performance. By increasing the number of independent parameters to possible eight, the quality of the optimal solution can be increased, with a complex mathematical procedure.
2. It is recommended to use an optimal model of the MDBP mechanism for factory design because it is an important design requirement.
3. Improving the model can be done by introducing the constraint function of internal forces in the MDBP which would require the extension of this task in the domain of static analysis.
4. The SQP procedure has given a slightly more accurate solution which is a result of a freely adjustable step. The formal procedure limits the accuracy (quality of solutions) by selecting the interval of indetermination. The quality of a solution can be improved by increasing the number of search combinations.
5. The computing time of implementation in each case is less than one second.

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REFERENCES

1. Radić, M., Marinković, Z., Jovanović, M., 2002, *Dynamics and optimization of cranes*, University of Niš, Faculty of Mechanical Engineering, scientific monograph, Niš (in Serbian)
2. Jain, A., Issac, K.K., 2003, *Optimal Design of Front End Loader Attachment for Tractors*, Proc. Eleventh National Conference on Machines and Mechanisms NaCoMM 2003, Indian Institute of Technology Delhi, New Delhi.
3. İpek, L., 2006, *Optimization of backhoe-loader mechanisms*, Master Thesis, Middle East Technical University, Turkey, 71 pp.
4. Zhang, R., Qi, J., Cai, Y., 2007, *Optimum Design of the Working Mechanism of Loader With Ant Colony Algorithm (ACA)*, Proc. Fourth International Conference on Mechatronics and Automation ICMA 2007, Harbin, China, pp 3066 – 3070.
5. Cao, X., Cleghorn, W., 2011, *Parametric Optimization of Eight-bar Mechanism of a Wheel Loader Based on Simulation*, Information Technology Journal 10(9), pp. 1801-1808.
6. Papazov, P. S., 1975, *Optimal Design of Electromagnetic Systems*, Tehnika, Sofia.
7. Vujčić, V., Ašić, M., Miličić, N., 1980, *Matematičko programiranje*, Matematical Institute, University of Belgrade.
8. Yu, Y., Lianguan, S., Mujun, L., 2010, *Optimum design of working device of wheel loader*, Proc. First International Conference Mechanic Automation and Control Engineering MACE 2010, Wuhan, China.
9. Xiuhua, G., Yunchao, W., Erzhong, A., Jiawei, H., 2007, *Optimization of the Working Device of Loader Based on ADAMS*, Computer Simulation Journal, 1(1).
10. Zhang, R., Qi, J., Cai, Y., 2008, *Intelligent optimum design of the working mechanism of loader*, Proc. Seventh World Congress on Intelligent Control and Automation WCICA 2008, Chongqing, China.
11. *Komatsu WA320,* http://www.komatsu.com/ce/products/pdfs/WA320-5.pdf, (accessed January 25, 2014).
12. Arora, S. J., 2007, *Optimization of Structural and Mechanical Systems,* University of Iowa, Iowa, 595 pp.
13. Venkataraman, P., 2009, *Applied Optimization with MATLAB Programming*, Wiley, 544 pp.

OPTIMALNA SINTEZA MANIPULATORA KORISTEĆI DVE UPOREDNE METODE

U radu je data programska realizacija za traženje optimalne geometrije ravanskog Z-mehanizma. Rad pokazuje matematičku proceduru definisanja funkcije cilja, funkcija ograničenja, oblasti pretraživanja kojima se rešava zadatak optimizacije. Polazeći od rešenja u praksi, dat je numerički primer određivanja optimalnog dizajna sa četiri parametra optimizacije. Svi parametri optimizacije su geometrijski na mehanizmu za određivanje nagiba kašike. Zadatak je rešavan dvema različitim, numerički metodama - metodom formalnog pretraživanja hiperprostora (metoda pasivnog skeniranja) i aproksimativnom metodom kvadratnog sekvencijalnog programiranja – SQP (primenom fminmax funkcije iz Matlabovog optimizacionog toolbox-a). Verifikacija rešenja je vršena animacijom u programu za geometrijsko modeliranje. Rezultati su grafički ilustrovani.

Ključne reči: *Pasivno traženje, Z - mehanizam, utovarivač, rudarska mašina, optimizacija mehanizma, numeričko rešavanje, SQP*