Marko Todorović
Teaching Assistant
University of Kragujevac
Faculty of Mechanical And Civil Engineering in Kraljevo

Goran Marković
Associate Professor
University of Kragujevac
Faculty of Mechanical And Civil Engineering in Kraljevo

Mile Savković
Full Professor
University of Kragujevac
Faculty of Mechanical And Civil Engineering in Kraljevo

Nebojša Zdravković
Associate Professor
University of Kragujevac
Faculty of Mechanical And Civil Engineering in Kraljevo

Goran Pavlović
Research Associate
University of Niš
Faculty of Electronic Engineering

Actuator placement optimization for hydraulic scissor lift

Choosing the optimal hydraulic cylinder and its placement within the mechanism of hydraulic scissor lift is the problem that can be solved using metaheuristic optimization algorithms, among which is the Snake optimizer. Hydraulic cylinders are standardized within manufacturers production programme, and their characteristics are usually known. The optimization algorithm will be used to evaluate characteristics and pick the optimal hydraulic cylinder for the defined mathematical model of hydraulic scissor lift, as well as find its optimal placement within the mechanism.

Keywords: *Hydraulic scissor lift, Snake Optimizer, Actuator placement optimization*

1. INTRODUCTION

Scissor lifts are transportation devices, that employ scissor mechanism, used for reaching high, hardly approachable areas or objects. They can be seen in various warehouses where they are used for reaching items on high shelves, maintenance of the lighting and wireing equipment spread over the high ceiling, as well as workshops where they can be sued for lifting heavy objescts such as cars during the inspection or maintenance.

The scissor lift iteslf, presented in fugure 1, is consisted of a platform on top of which the load is being placed. Additonal special devices can be mounted on the platform depending on the purpose of the platform, such as rails, or measuring equipment. Platform is layed on top of the scissor mechanism which can contain one or more scissor pairs usually powered by hydraulic or pneumatic actuator. The mechanism is then placed on top of the frame in the base of the platform. The first scissor pair on the bottom is connected with pin support on one end, and a roller or a slider on the other end. One scissor pair contains two beams connected in the middle with a pin which enables both beams to rotate. The last scissor pair is connected to the top platform in the same way as the first one is connected to the base frame. The base frame can be either installed directly to the floor of the fascility in which case the platform is fixed and stationary. Stationary scissor lifts are usually placed in workshops. On the other hand, the base frame can be mounted on top of movable carts in which case they are mobile, and they can easily be transported to varios places if needed.

Considering that these devices are so common, it is no wonder they attracted the attention of many researchers. In the paper [1] authors introduced a compact algorithm for desinging a hydraulic scissor lifting platform while the general guidelines for designing in fabrication were given in [2] and [3], and detail mathematical analysis was introduced in [4].

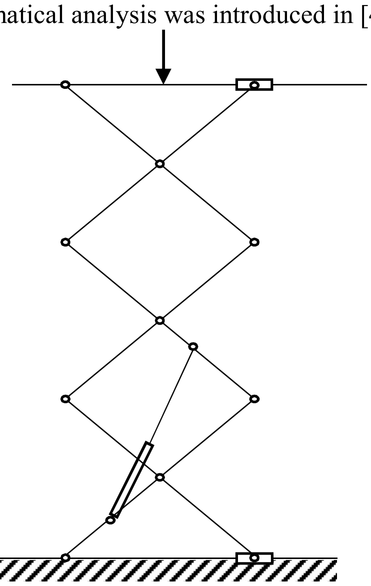

Figure 1. Illustration of the hydraulic scissor lift

Flourishing development of computer technology and new, metaheuristic optimization algorithms, such as Harris hawks optimization algorithm [5], presented the tool that can easily be used for developing more optimal structures. In paper [6] the theoretical optimal shape of a hydraulic scissor lift mechanism members was obtained using the Harris hawks optimization method. These, metaheuristic optimization methods are searching for

Correspondence to: Marko Todorović, teaching assistant
Faculty of Mechanical and Civil Engineering in Kraljevo, Dositejeva 19, 3600 Kraljevo, Serbia
E-mail: todorovic.m@mfkv.kg.ac.rs

optimal solutions by randomly selecting the values within defined searching space, and transform those values through iterations obtaining minimal value of the required object function.

However, choosing the optimal size and placment of an actuator represents specific problem since the actuators are made in sizes standardized by manufacturers programme. One way for solving this problem will be represented in this paper, and it will be used alongside the novel metaheuristic optimization algorithm called Snake optimizer [7], which will be briefly introduced in the upcoming chapter.

2. SNAKE OPTIMIZER

The Snake optimizer which is in detail presented in the paper [7] is swarm based, nature inspired metaheuristic optimization algorithm which mimics the the mating process of snakes.

Snakes are cold bloded animals and for mating process to occur, a couple of conditions need to be met: there has to be cold enough, and there has to be enough food. If either of those conditions aren't met, the mating won't occur. In this the authors of the algorithms saw carateristic phases of metaheuristic algorithms, exploration and exploitation phase.

The exploration phase represents the enviromental factors such as temperature and food. Exploitation phase occurs when both the temperature is low enough and there is enough food, and it is consisted of two modes: Fight mode, and Mating mode. In fight mode, each male fights with other males for the best female, and each female searches for the best male. In the mating mode, which occurs between each pair. If this happens during the searching phase, snakes lay eggs and new snakes appear.

When the algorithm is started, like in every other metaheruristic algorithm, the random initial population is being generated, after which the population is being divided into male and female groups, each containing half of the initial population. He best male, female, and food position is being calculated, as well as the temperature ($Temp$) and food quantity (Q) which are described using the following expressions:

$$Temp = \exp\left(-\frac{t}{T}\right) \quad (1)[7]$$

$$Q = c_1 \cdot \exp\left(\frac{t-T}{T}\right) \quad (2)[7]$$

…where the variables are: T – total number of iterations; t – the number of the current iteration, c_1 – constant which equals 0,5.

Exploration phase begins since there's no food which reflects in $Q < 0{,}25$. Then the snakes randomly search the area for food and update their position accordingly:

$$X_{i,m}(t+1) = X_{rand,m}(t) \pm c_2 \times A_m \times ((X_{\max} - X_{\min}) \times rand + X_{\min}) \quad (3)[7]$$

…where the variables reffer to: $X_{i,m}$ – the position of i-th male snake, $X_{rand,m}$ – the position of randomly seleceted male candidate, $rand$ – is random number in the [0,1] interval, c_2 is a constant that equals 0,05, and A_m is the ability of the male to find the food, and it can be calculated with the following expression:

$$A_m = \exp\left(-\frac{f_{rand,m}}{f_{i,m}}\right) \quad (4)[7]$$

…where: $f_{rand,m}$ is the value of the object function for the random male candidate, and $f_{i,m}$ is the value of the object function of the i-th male candidate. Female group members also update their location in the same way, following the (3) and (4).

When there is enough food, meaning the $Q > 0{,}25$, but the temperature is high ($Temp > 0{,}6$), the snakes, both male and female, will update their current position thowards it:

$$X_{i,j}(t+1) = X_{\text{food}}(t) \pm c_3 \times Temp \times (X_{\text{food}} - X_{i,j}(t)) \quad (5)[7]$$

…where: $X_{i,j}$ represents the position of individual for both male and female groups, c_3 is the constant that equals 2, and X_{food} represents the position of the best member of the current population.

If the temperature is higher then 0,6, and there is plenty of food, the fighting or mating mode starts. Fighting mode is moddeled in the following way:

$$X_{i,j}(t+1) = X_{i,j}(t) \pm c_3 \times F \times rand \times \left(X_{best,j} - X_{i,m}(t)\right) \quad (6)$$

…where:

$$F = \exp\left(-\frac{f_{best}}{f_i}\right) \quad (7)$$

…f_{best} – is the best male or female position, depending of which population the current snake belongs to.

The mating mode is modeled as:

$$X_{i,m}(t+1) = X_{i,m}(t) \pm c_3 \times M_m \times rand \times (Q \times X_{i,f}(t) - X_{i,m}(t)) \quad (8)[7]$$

$$X_{i,f}(t+1) = X_{i,f}(t) \pm c_3 \times M_f \times rand \times (Q \times X_{i,m}(t) - X_{i,f}(t)) \quad (9)[7]$$

…where:

$$M_m = \exp\left(-\frac{f_{i,f}}{f_{i,m}}\right); M_f = \exp\left(-\frac{f_{i,m}}{f_{i,f}}\right) \quad (10)[7]$$

…represent the mating abilities of male and female. If the egg hatch, the worst male and female are being replaced with new random population members generated within the searching area.

3. ACTUATOR FORCE

The expression for calculating the force which actuator needs to bring into the system in order to achieve the lifting of the platform can be obtained in various ways, either by using writing and solving the equations of static equilibrium, or by using the principle of conservation of energy. Writing and solving the equations of static equilibrium can be challenging, and this method is prone to inducing errors especially if the analyzed platform is consisted of multiple levels, so using the principle of conservation of energy is the prefered method.

The observed hydraulic scissor lift, displayed in figure 2, is consisted of four scissor pairs (has four levels), and it is being powered by a single actuator $\overline{BE}$ pinned to the mechanism members on both ends. Load T is being placed on top of the scissor lift, centered on the top platform $\overline{PM}$. Friction in joints and connections are being neglected, as well as the weight of the platform itself, and the platform is placed on the flat surface where the gravity acts parallel to the *y* axis.

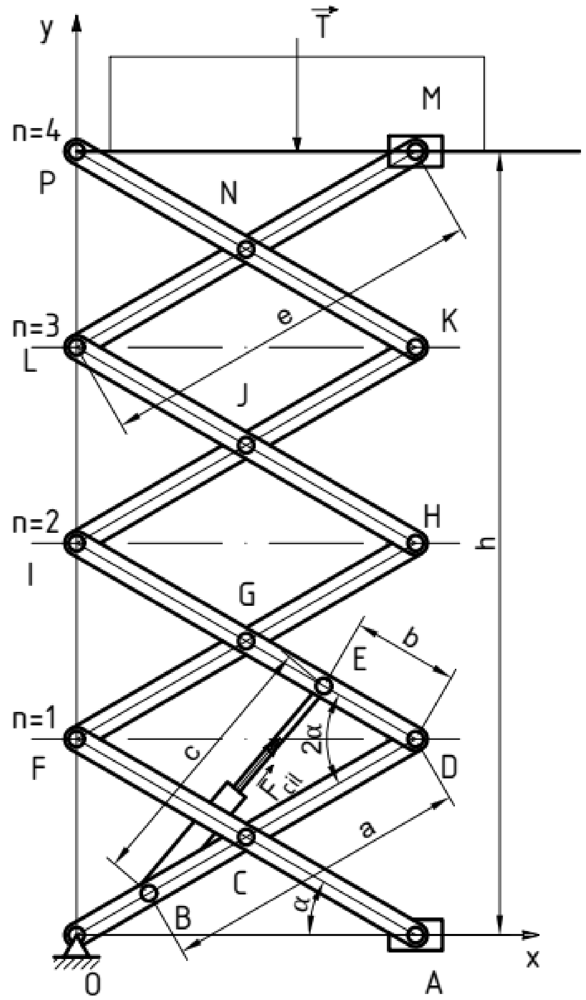

Figure 2. Hydraulic scissor lift with four scissor pairs

Following the principle of conservation of energy [8], based on the Fig. 2, the following equation can be written:

$$-T \cdot \frac{\mathrm{d}h}{\mathrm{d}l} + F_{\mathrm{cil}} = 0 \tag{11}$$

If the centre of the coordinate system is set in the pin O, the coordinates of the actuator pins are as follows:

$$x_B = (e - a) \cdot \cos(\alpha)\,; \tag{12}$$
$$y_B = (e - a) \cdot \sin(\alpha)\,; \tag{13}$$
$$x_E = (e - b) \cdot \cos(\alpha); \tag{14}$$
$$y_E = (e + b) \cdot \sin(\alpha). \tag{15}$$

Length of the actuators projections to the axis of the coordinate system can be expressed as:

$$c_x = |x_E - x_B| = |(a - b) \cdot \cos(\alpha)| \tag{16}$$

$$c_y = |y_E - y_B| = |(b + a) \cdot \sin(\alpha)| \tag{17}$$

The total length of the actuator, squared, following (16) and (17), is:

$$c^2 = (a - b)^2 - 4 \cdot a \cdot b \cdot \frac{h^2}{n^2 \cdot e^2} \tag{18}$$

When the squared height of the scissor platform is expressed from the (18), the following expression is obtained:

$$h^2 = \frac{(c^2 - (a - b)^2) \cdot n^2 \cdot e^2}{4 \cdot a \cdot b} \tag{19}$$

From (19), the first derivate of hight d*h*/d*c* is:

$$\frac{\mathrm{d}h}{\mathrm{d}c} = \frac{e \cdot n \cdot c}{2 \cdot a \cdot b} \cdot \sqrt{\frac{a \cdot b}{c^2 - (a - b)^2}} \tag{20}$$

When the (20) is replaced in the (11), actuation force can be expressed as follows:

$$F_{cil} = T \cdot \frac{c \cdot n \cdot e}{2 \cdot a \cdot b} \cdot \sqrt{\frac{a \cdot b}{c^2 - (a - b)^2}} \tag{21}$$

Considering that the length of the actuator can be expressed using the law of cosines:

$$c = \sqrt{a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos(2 \cdot \alpha)} \tag{22}$$

…it can be noticed that the intensity of the actuation force depends on the inclination angle of the members of the scissor mechanism, as well as the position in which the actuator is placed. There are two characteristic position in which the platform can be found in, the first is when it is in its lowest position, where the angle α has the lowest value and the height on which the top platform is placed at is the lowest as well. The other characteristic position is its highest position, when the agle α takes its maximum value, as well as the height on which is the top platform. The diagram diplayed on fig. 3 shows how the actuator force changes with the change of the inclination angle α.

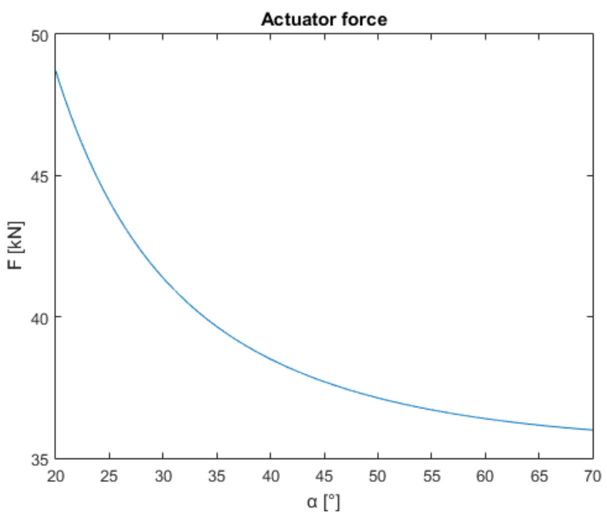

Figure 3. Actuator force diagram

By observing the diagram it can be concluded that the actuation force has the highest intensity when the platform takes the lowest position.

4. OBJECT FUNCTION AND CONSTRAINTS

Choosing optimal cylinder and its placement might seem as trivial task, but there are couple of contradictory requirements. The lower the force that actuator needs to produce the smaller diameter of the piston is required, but the stroke needs to be longer. The longer the stroke needs to be, the heavier hydraulic cylinder is needed, and the danger of losing local stability within the cylinder piston is increased.

Instead of using directly the force or the stroke length for choosing the optimal hydraulic cylinder, the total mass of the cylinder can be used as object function as it is a factor that depends on both, length of the stroke, as well as the needed force which, according to (21), depends on the placement within the mechanism.

The optimal values of variables which will be searched with the use of the Snake optimizer will be the position of the actuator *a*, and *b*. Based on these values, the actuator force can be calculated in the mentioned characteristic positions of the scissor lift. Borders of the searching area are set to be the lengths of the scissor mechanism legs: $a \in [0, e]$, $b \in [0, e]$.

However, manufacturares of the hydraulic cylinders often publish catalogues which contain important characteristics of the hydraulic cylinders they produce. Custom hydraulic cylinders can be built, but that adds to the cost and complexity of production, and also further maintenance during the hydraulic scissor lift life cycle. These data can be collected within a database from which the optimization algorithm, Snake optimizer in this case, can use the needed data for choosing the optimal hydraulic cylinder by comparing the relevant characteristics. These information can be stored in the table formated as shown in the table 1, which is created out of data from [9].

When the force is calculated using (21) for the chosen variables *a* and *b* provided by the optimization algorithm the first cylinder from the table 1 that can handle the force of equal or higher intensity is being evaluated.

Knowing that the length of the cylinder is the shortest when the platform is in its lowest position, variables *a* and *b* must be such that when put into the (22) length of the cylinder *c* is not smaller then the minimal dimension of the chosen cylinder. For this to be ensured, the following constraint g is defined as:

$$g = c_{cil} - c_{min} > 0; c_{min} = c(\alpha = \alpha_{min}) \qquad (23)$$

The chosen cylinder must also have permissible stroke that is not shorter then c_{max}, $c_{max} = c(\alpha = \alpha_{max})$.

The evaluated hydraulic cylinder has all the needed characteristics defined in the database, and its mass can be calculated:

$$m_{total} = m_6 + m_7 \cdot \frac{c_{max} - c_{cil}}{100} \qquad (24)$$

Since the mass of the cylinder should be minized, the (24) represents the object function. If the constraint is breached, the punishment function is added, so the final expression for the object function is:

$$o = m_{total} + g \cdot 10^6 \qquad (25)$$

In every iteration of the optimization process the hydraulic cylinders from the database displayed in table 1 are being evaluated, and the mass of the chosen cylinder from the current iteration is being carried and compared to the mass in next iteration. If the mass of the cylinder in the current iteration is smaller then the mass of the cylinder chosen in previous iteration, the new mass is replacing the one from previous iteration, and the variables *a* and *b* for which the mass was calculated are being stored as the best current solution. After many iterations the optimization algorithm passes through, the final, optimal values of *a* and *b* are purposed by the optimization algorithm which determine the optimal position of the actuator, as well as all other actuator characteristics which correspond to those in table 1.

5. RESULTS

The optimization was tested on a multilevel hydraulic sscissor lift with four scissor pairs, as displayed in fig. 2. The needed characteristics of the hydraulic scissor lift which were used in optimization are displayed in table 2, and the cylinder characteristics were chosen from the table 1.

Table 2. Characteristics of the hydraulic scissor lift

Characteristic		Value	Unit
T	Active load	5,886	kN
e	Scissor leg length	1000	mm
n	Number of levels	4	-
$\alpha_{\min}$	Minimal inclination angle	20	°
$\alpha_{\max}$	Maximal inclination angle	70	°

The maximum number of itrerations for the Snake optimizer to complete is set to 1000, and the number of searching agents is set to be 30. The problem is two dimensional since only two variables are being searched, and the boundaries within the variables are being searched are $a \in [0, 1000]$, and $b \in [0, 1000]$.

The Snake optimizer completed all 1000 iterations in 36,441 seconds with convergence curve which is displayed in Fig. 4.

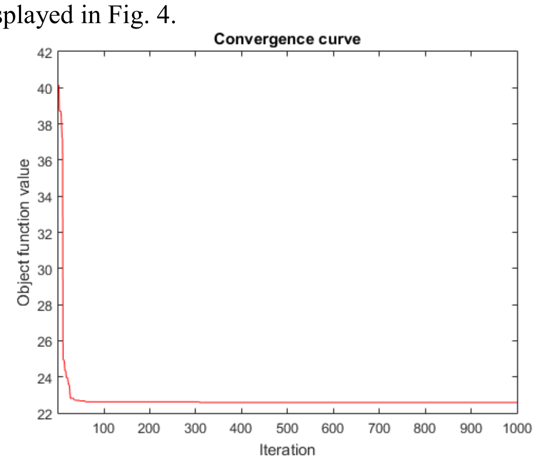

Figure 4. Convergence curve

The result of the optimization are the values of the optimized variables:

- $a = 234{,}6382$ mm;
- $b = 391{,}5275$ mm.

The characteristics of the optimal cylinder that came out as a product of this optimization are displayed in table 3.

Table 3. Characteristics of the optimal hydraulic cylinder

Characteristic	Optimal cylinder
Piston [mm]	100
Rod [mm]	70
Force at 200 bar [kN]	76,1028375
Permissible stroke at 200 bar [mm]	850
Minimal dimension	300

The parameters that need to be satisfied in order for this cylinder to be adequate for the task, considering the position of the hydraulic cylinder, and their values are displayed in table 4.

Table 4. Parameters calculated for the optimal placement of the hydraulic cylinder

Characteristic	Value
F_{cil} [kN]	48,7058
$c_{\max}$ [mm]	590,8450
$c_{\min}$ [mm]	260

6. CONCLUSION

In engineering and machinery design most of the parts considered during the design process are standardized either by official standard or by manufacturers product programme. Metaheuristic optimization algorithms are powerful tool which can speed up the designing process. By connecting this tool with adequate database which contains characteristics of standardized parts, they can help picking the item with optimal characteristics for the given mathematical model, automatically.

However, it should be noted that efficency of this approach depends on the database as well. The more information it contains, the more optimal result the optimization algorithm can provide.

The results of the optimization shown in table 3 and table 4, when compared to available data in table 1 show that the first smallest by dimaeter hydraulic cylinder that can handle the load is not always the optimal one, since there are also other factors to take into consideration, such as minimal length of the hydraulic cylinder, and permissible stroke at the given pressure.

The mathematical model can be extended to other types of load, such as the case when the hydraulic scissor lift is placed on inclined surface, or when the concentrated moment acts on top top platform. The mathematical model can also be completed with the weight of the scissor lift , which is the direction in which the further research of the topic is suggested.

ACKNOWLEDGMENT

This paper is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia through Contract No. 451-03-68/2022-14/200108.

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Table 1. Characteristics of hydraulic cylinders

1	2	3	4	5	6	7	8
Piston [mm]	Rod [mm]	Theoretical force at 210 bar [kN]	Force at 200 bar [kN]	Permissible stroke at 200 bar [mm]	Mass [0 stroke] m_6 [kg]	Mass/stroke m_7 [kg/100 mm]	Minimal length c_{min} [mm]
32	18	11.55	10.44548	115	1.5	0.7	155
32	22	8.91	8.057947	220	1.5	0.8	155
40	22	18.41	16.65309	145	2.5	0.9	180
40	28	13.46	12.17645	305	2.5	1	180
50	28	28.3	25.60636	205	4	1.3	200
50	36	19.86	17.96623	425	4	1.6	200
63	36	44.09	39.88684	285	6.5	1.8	235
63	45	32.06	29.00861	535	6.5	2.2	235
80	45	72.16	65.28429	370	11	2.9	260
80	56	53.83	48.70581	670	11	3.5	260
100	56	113.21	102.4254	470	19.5	4.7	300
100	70	84.12	76.10283	850	19.5	5.8	300
125	70	176.89	160.0397	605	32.5	6.4	340
125	90	124.11	112.2889	1155	32.5	7.7	340
140	90	189.67	171.6044	970	49	9.7	390
140	100	158.34	143.2524	1265	49	11	390
160	100	257.3	232.7851	1040	72.5	12.7	435
160	110	222.66	201.4486	1320	73	14	435
180	110	334.82	302.9191	1090	113	17.4	500
180	125	276.68	250.3186	1510	113.5	19.5	500
200	125	402.03	363.7267	1290	149.5	22	545
200	140	336.46	304.4113	1715	150	24.4	545