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Research of relationships between the technical parameters of industrial manipulators

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Abstract. Industrial manipulators have to become an integral part of modern construction production, playing a key role in the automation and optimization of production processes. When designing and using industrial manipulators, it is important to know the various parameters that interact with each other and affect the overall productivity and efficiency of the production line in which industrial manipulators operate. In the design of the robot process and construction production, it is necessary to know the technical requirements that need to be met by the robot system. Therefore, when designing industrial robots and manipulators, it is necessary to take into account the shape, dimensions, and weight of the building structures with which the industrial robot will work, as well as their physical and mechanical properties. These parameters will determine the general scheme and layout of the robot's components, the design of the clamping device and clamping force, the type of drive and its control principle. This paper is devoted to the identification of regularities between the main technical parameters of reach and lifting capacity of general-purpose industrial manipulators. Regression analysis with the use of hyperbolic and cubic splines is applied. The regression equations were solve based on the minimization of the total squared deviation of the correlation function.

The results of the work will be useful for developers of industrial robots and researchers who are engaged in the development of robotic technological lines and productions.

Keywords: manipulator parameters, relationships between parameters, industrial manipulators, correlation theory, least squares method.

INTRODUCTION

Identifying regularities between the parameters of robots and manipulators is a difficult and important task facing developers of such systems [1-2]. This problem is especially important in the development of robotic systems for construction production [3-4]. When creating robotic modular systems and when developing drive systems, it is also necessary to know the pressure forces on the drive links in advance [5] depending on the parameters of the robot's executive system. For this to need knows the relationship between the main technical parameters of robots and manipulators. Since research in this direction in robotics is quite scarce, it was suggest investigating the existing designs of industrial manipulators and establishing mathematical dependencies for their further analysis.

PURPOSE OF THE ARTICLE

Investigation of technical parameters of industrial manipulators and determination of the relationships between the parameters of load capacity and reach under consideration.

PRESENTING MAIN MATERIAL

The main technical parameters of industrial robots and manipulators include rated load capacity, reach (reach of the working body), power, number of degrees of mobility, type of workspace [6].

The load capacity characteristic defines the largest mass of cargo or technical equipment that a robot can move while ensuring the desired performance and safety [6-7]. The reach characterized by the space in which the working body of a robot or manipulator is able to perform the specified functions in accordance with the purpose of the robot [8]. Therefore, we note that lifting capacity and reach are the main technical characteristics based on which mechanical robotic systems are developed.

The initial conditions for construction robotization are the procedure for developing technical requirements for the design of a robot or manipulator, taking into account the specifics of construction. For example, when developing construction mechanization tools, it is necessary to take into account the shape, dimensions and weight of building structures, as well as their physical and mechanical properties [4, 7]. These indicators will determine the general scheme and layout of the robot's components, the type and design of the drive system, and the control principle. All of this indicates that the design of robots and manipulators for construction and installation work will based on the analysis of the technical parameters of robotics means and the technical parameters of construction processes.

In the following, we will consider the methodology for determining the relationships between the technical parameters of the reach and the lifting capacity of stationary manipulators of industrial robots of a typical design with five or six degrees of mobility (Fig. 1) and similar structure. For comparison, the technical parameters of industrial manipulators manufactured by Kawasaki (Japan), ABB (Sweden), and KUKA (Germany) presented in Table 1.

Table 1 shows the data for six manipulators from three manufacturers in order of increasing load capacity. Table 1 shows that KUKA does not indicate power values in the technical characteristics of its robots, so a power comparison for such designs will not be possible. All of the

Table 1. Technical parameters of industrial manipulators

№	Robot model	Load capacity, kg	Reach, mm	Power, kW	Weight, kg	Number of degrees of movement
1	Kawasaki RS003N	3	620	1,5	20	6
2	Kawasaki RS007N	7	730	2,2	35	6
3	Kawasaki RS015X	15	3150	6	545	6
4	Kawasaki RS080N	80	2100	25	555	6
5	Kawasaki BXP165N	165	2325	50	1350	6
6	Kawasaki BXP210L	210	2597	15	870	6
7	ABB IRB 2600ID	15	1850	2,5	273	6
8	ABB IRB 4400	60	1960	1,33	1040	6
9	ABB IRB 460	110	2400	4,31	925	5
10	ABB IRB 6620	150	2200	2,8	880	6
11	ABB IRB 6790	235	2650	26	1200	6
12	ABB IRB 6700	250	3700	50	1280	6
13	KUKA KR 8 R2100-2 arc HW	8	2101	-	260	6
14	KUKA KR 16 R2010-2	16	2013	-	260	6
15	KUKA KR 20 R1810 F	20	1813	-	250	6
16	KUKA KR 120 R1800 nano	120	1803	-	684	6
17	KUKA KR 120 R2700-2	120	2701	-	1069	6
18	KUKA KR 210 R3100-2	210	3100	-	1139	6

Fig. 1. Industrial manipulator ABB IRB 6620

industrial manipulators under consideration have an electric gear drive.

To evaluate the technical qualities of these manipulators, all their designs were compared by the correlations between technical characteristics, which are called comparable criteria. The criterion of the ratio of load capacity Q to reach D shows how much of the cargo mass moved per 1 meter of reach:

$$K_1 = \frac{Q}{D}. \quad (1)$$

In Fig. 2 shows a histogram with the distribution of the K_1 criterion for different designs of the considered manipulators. The histogram below shows how the value of the criterion increases with increasing load capacity for each of the three groups of manipulators K_1. The highest values of the K1 criterion are typical for manipulators with a large lifting capacity from 100 to 250 kg. This means that such systems use a more complex drive design that provides significant torque values.

The criterion of the ratio of lifting capacity Q to mass m shows how much of the load mass perceived by a unit of mass of the manipulator's metal structure:

$$K_2 = \frac{Q}{m}. \quad (2)$$

From the histogram shown in Fig. 3 histogram shows that the designs of manipulators with a large lifting capacity have higher values of the criterion K_2 of the ratio of lifting capacity to mass. This may mean that such systems are more massive. It should be note that the designs of the industrial manipulators Kawasaki RS003N and Kawasaki RS007N differ in the considered K_2 indicator from similar competing systems, as can be seen in Fig. 3. This explained by the fact that the designs of these robots have a frame structure different from other similar

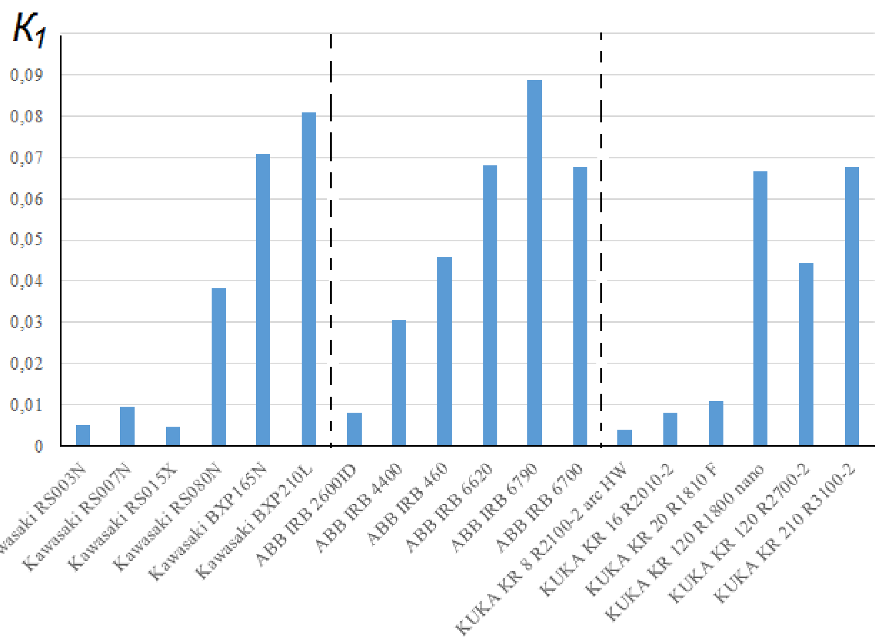

Fig. 2. The ratio of the criterion K_1

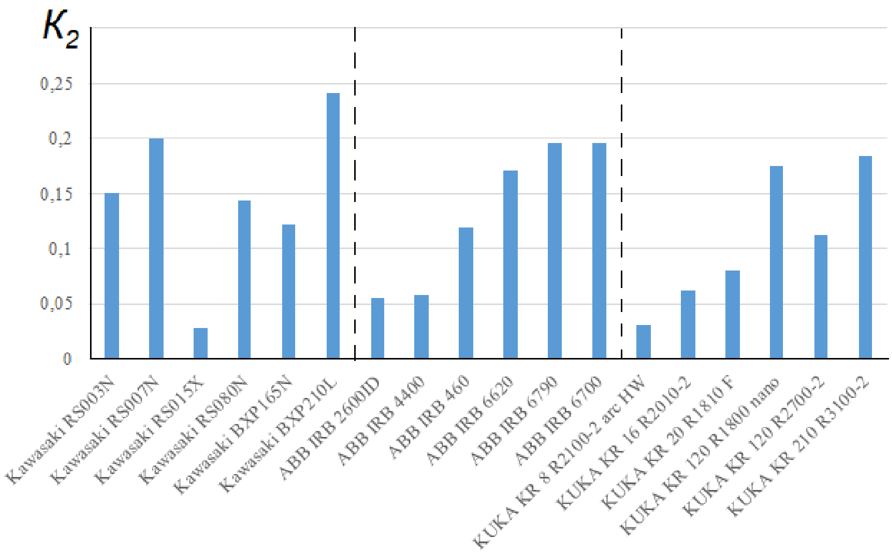

Рис. 3. The ratio of the criterion K_2

schemes of low load capacity. These robot schemes are built on frames with a higher load capacity, but with a drive of lower traction capacity. To determine the interdependence between the parameters of the manipulators, we will determine the regression equation using the method of least squares [9]. The essence of such a technique is to determine a polynomial that will provide the minimum sum of squares of the differences between the actual values of the observed quantity and its calculated value:

$$U = \sum_{i=1}^{n} \varepsilon_i^2 \to \min . \quad (3)$$

Let us use the following hyperbola equation as a polynomial [4]:

$$y = a - \frac{b}{x}, \quad (4)$$

where: a, b is unknown coefficients in the equation.

As a variable parameter x_i in the function of (4) specify the reach or departure parameter, and as the value of the function y_i will be the value of the carrying capacity.

Let us express equality (3) in terms of the hyperbole equation (4):

$$U = \sum_{i=1}^{n} (y_i - a + \frac{b}{x_i})^2 \to \min . \quad (5)$$

To find the unknown coefficients, let's determine the derivatives of these coefficients:

$$\frac{d}{da}\sum_{i=1}^{n}(y_i - a + \frac{b}{x_i})^2 = = -2(\sum y_i - an + b\sum \frac{1}{x_i}) = 0; \quad (6)$$

$$\frac{d}{db}\sum_{i=1}^{n}(y_i - a + \frac{b}{x_i})^2 = 2(\sum y_i\left(\frac{1}{x_i}\right) - -a\sum \frac{1}{x_i} + b\sum \left(\frac{1}{x_i}\right)^2) = 0. \quad (7)$$

To calculate equations (6) and (7), a table was compile in accordance with the specified form of correlation between departure and carrying capacity data (Table 2).

Taking into account the data from Table 2, equations (6) and (7) will be as follows:

$$\begin{cases} 1794 - 18a + 9{,}933b = 0; \\ 719{,}61 - 9{,}933a + 7{,}613b = 0. \end{cases} \quad (8)$$

From the system of equations (8), it is found that a = 169,6; b = 126,8.

The result was a regression dependence for predicting the lifting capacity parameter depending on the maximum reach of the manipulator, kg:

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$$Q(L) = 169{,}6 - \frac{126{,}8}{L}, \qquad (9)$$

where: L is maximum reach or reach of the manipulator, m.

To determine the reliability of the obtained correlation, we determine the covariance ratio between a given carrying capacity parameter and its predicted value by the Pearson's coefficient, which is equal to the square root of the variance of the studied values [10]:

$$\eta = \sqrt{\frac{\sigma_{yx}^2}{\sigma_y^2}}, \qquad (10)$$

where: $\sigma_{yx}^2 = \frac{\sum (Q(L) - \bar{y})^2}{n}$; $\sigma_y^2 = \frac{\sum (y - \bar{y})^2}{n}$.

Let us determine the average value of the load-carrying capacity for the considered manipulator designs according to their passport values:

$$\bar{y} = \frac{\sum y}{n}, \qquad (11)$$

where: $\sum y$ the total value of the carrying capacity for all observations;
n the total number of observations for a given value.

The results of calculating the parameters of Pearson's coefficient are shows in Table 3.

The reliability of the correlation was assess by N. Leontief's inequality [4]:

$$\frac{\eta}{\mu} \geq 4{,}0, \qquad (12)$$

where: $\mu = \pm \frac{1 - \eta^2}{\sqrt{n}}$ the average error of the correlation ratio.

Table 2. Data of the regression function for the hyperbolic polynomial

№	$y(Q)$, kg	$x(D)$, m	$\frac{1}{x_i}$	$\left(\frac{1}{x_i}\right)^2$	$\left(\frac{1}{x_i}\right)y$
1	3	0,620	1,612903	2,601457	4,83871
2	7	0,730	1,369863	1,876525	9,58904
3	8	2,101	0,475964	0,226542	3,80771
4	15	3,150	0,317460	0,100781	4,76190
5	15	1,850	0,540541	0,292184	8,10811
6	16	2,013	0,496771	0,246781	7,94834
7	20	1,813	0,551572	0,304232	11,03144
8	60	1,960	0,510204	0,260308	30,61224
9	80	2,100	0,476190	0,226757	38,09524
10	110	2,400	0,416667	0,173611	45,83333
11	120	1,803	0,554631	0,307616	66,55574
12	120	2,701	0,370233	0,137073	44,42799
13	150	2,200	0,454545	0,206612	68,18182
14	165	2,325	0,430108	0,184992	70,96774
15	210	2,597	0,385060	0,148271	80,86253
16	210	3,100	0,322581	0,104058	67,74194
17	235	2,650	0,377358	0,142399	88,67925
18	250	3,700	0,270270	0,073046	67,56757
$n = 18$	$\sum y$ = 1794	$\sum x$ = 39,813	$\sum 1/x$ = 9,932922	$\sum (1/x)^2$ = 7,613245	$\sum (1/x)y$ = 719,6106

From the given equations it was found that η = 1,33, a μ = -0,18. Then:

$\frac{1,33}{-0,18} = -7,34 < 4,0$ the condition is not fulfilled.

The regression function based on the next cubic polynomial was research:

$$y = a + bx + cx^2 + kx^3, \quad (13)$$

where: *a*, *b*, *c*, *k* the regression coefficients.

The objective function (3) taking into account the given cubic polynomial will be:

$$U = \sum_{i=1}^{n} (y_i - a - bx_i - cx_i^2 - dx_i^3)^2 \to \min \quad (14)$$

The derivatives for these coefficients will be as follows:

$$\frac{d}{da}\sum_{i=1}^{n}(y_i - a - bx_i - cx_i^2 - kx_i^3)^2 = -2(\sum y_i - na - b\sum x_i - c\sum x_i^2 - k\sum x_i^3) = 0; \quad (15)$$

$$\frac{d}{db}\sum_{i=1}^{n}(y_i - a - bx_i - cx_i^2 - kx_i^3)^2 = -2(\sum x_i y_i - a\sum x_i - b\sum x_i^2 - c\sum x_i^3 - k\sum x_i^4) = 0; \quad (16)$$

$$\frac{d}{dc}\sum_{i=1}^{n}(y_i - a - bx_i - cx_i^2 - kx_i^3)^2 = -2(\sum x_i^2 y_i - a\sum x_i^2 - b\sum x_i^3 - c\sum x_i^4 - k\sum x_i^5) = 0; \quad (17)$$

Table 3. Variance values for the hyperbolic regression function

№	y	$(y-\bar{y})$	$(y-\bar{y})^2$	Q(L)	$(Q(L)-\bar{y})$	$(Q(L)-\bar{y})^2$
1	3	-96,6667	9344,444	-34,9161	-134,582796	18112,53
2	7	-92,6667	8587,111	-4,09863	-4,09863014	16,79877
3	120	20,33333	413,4444	99,27277	99,27276761	9855,082
4	20	-79,6667	6346,778	99,66067	99,66067292	9932,25
5	15	-84,6667	7168,444	101,0595	101,0594595	10213,01
6	60	-39,6667	1573,444	104,9061	104,9061224	11005,29
7	16	-83,6667	7000,111	106,6094	106,6094386	11365,57
8	80	-19,6667	386,7778	109,219	109,2190476	11928,8
9	8	-91,6667	8402,778	109,2478	109,2477868	11935,08
10	150	50,33333	2533,444	111,9636	111,9636364	12535,86
11	165	65,33333	4268,444	115,0624	115,0623656	13239,35
12	110	10,33333	106,7778	116,7667	116,7666667	13634,45
13	210	110,3333	12173,44	120,7744	120,774432	14586,46
14	235	135,3333	18315,11	121,7509	121,7509434	14823,29
15	120	20,33333	413,4444	122,6544	122,6544243	15044,11
16	210	110,3333	12173,44	128,6968	128,6967742	16562,86
17	15	-84,6667	7168,444	129,346	129,3460317	16730,4
18	250	150,3333	22600,11	135,3297	135,3297297	18314,14
$n = 18$	$\sum y$ = 1794	$\sum(y-\bar{y})^2 = 128976$		$\sum(Q(L)-\bar{y})^2 = 213784,6$		
$\bar{y} = \sum y / n =$ 99,67		$\sum(y-\bar{y})^2 / n = 7165,33$		$\sum(Q(L)-\bar{y})^2 / n = 20377,4$		

$$\frac{d}{dk}\sum_{i=1}^{n}(y_i - a - bx_i - cx_i^2 - kx_i^3)^2 =$$
$$= -2(\sum x_i^3 y_i - a\sum x_i^3 - b\sum x_i^4 - c\sum x_i^5 - \quad (18)$$
$$-k\sum x_i^6) = 0.$$

Table 4 shows the calculated data for a given cubic polynomial.

Using the data in Table 4 and dependencies (15)-(18), the following system of equations was construct:

$$\begin{cases} 1794 - 18a - 39{,}8b - 97{,}8c - \\ -257{,}5k = 0; \\ 4715{,}1 - 39{,}8a - 97{,}8b - 257{,}5c - \\ -715{,}7k = 0; \\ 12978{,}5 - 97{,}8a - 257{,}5b - 715{,}7c - \\ -2085{,}9k = 0; \\ 37314{,}1 - 257{,}5a - 715{,}7b - 2085{,}9c - \\ -6339k = 0. \end{cases} \quad (19)$$

From the system of equations (19), it is found that a = 81,55; b = -200,89; c = 138,53; k = -20,33.

Taking into account the obtained coefficients, a regression equation was obtains for the dependence of the load capacity parameter on the reach for the considered industrial manipulators:

$$y = 81{,}55 - 200{,}89x + 138{,}53x^2 - 20{,}33x^3, \quad (20)$$

For equation (20), the variance was also determined and the Pearson test was evaluate. The results of the calculations are shows in the Table. 5.

The Pearson coefficient for this cubic spline (20) is η = 0,682, and the average error of the correlation ratio will be μ = 0,12. Then:

$\frac{0{,}682}{0{,}12} = 5{,}41 > 4{,}0$ - the condition is fulfilled.

From the above it follows that the cubic dependence will more accurately reflect the nature of the influence of the studied accessibility factor on the value of the carrying capacity.

Table 4. Regression function data for a cubic polynomial

№	*y(Q)*, kg	*x(D)*, m	x^2	x^3	x^4	x^5	x^6	$y \cdot x$	$y \cdot x^2$	$y \cdot x^3$
1	3	0,62	0,3844	0,2383	0,1477	0,09161	0,0568	1,86	1,1532	0,71498
2	7	0,73	0,5329	0,3890	0,2839	0,20730	0,1513	5,11	3,7303	2,72311
3	120	1,803	3,2508	5,8612	10,567	19,0536	34,353	216,36	390,09	703,345
4	20	1,813	3,2869	5,9592	10,804	19,5879	35,512	36,26	65,739	119,185
5	15	1,85	3,4225	6,3316	11,713	21,6699	40,089	27,75	51,3375	94,9743
6	60	1,96	3,8416	7,5295	14,757	28,9254	56,693	117,6	230,496	451,772
7	16	2,013	4,0521	8,1570	16,420	33,0536	66,536	32,208	64,8347	130,512
8	80	2,1	4,41	9,261	19,448	40,8410	85,766	168	352,8	740,88
9	8	2,101	4,4142	9,2742	19,485	40,9383	86,011	16,808	35,3136	74,1938
10	150	2,2	4,84	10,648	23,425	51,5363	113,37	330	726	1597,2
11	165	2,325	5,4056	12,568	29,220	67,9383	157,95	383,62	891,928	2073,73
12	110	2,4	5,76	13,824	33,177	79,6262	191,10	264	633,6	1520,64
13	210	2,597	6,7444	17,515	45,487	118,129	306,78	545,37	1416,32	3678,19
14	235	2,65	7,0225	18,609	49,315	130,686	346,31	622,75	1650,28	4373,26
15	120	2,701	7,2954	19,704	53,222	143,755	388,28	324,12	875,448	2364,58
16	210	3,1	9,61	29,791	92,352	286,291	887,50	651	2018,1	6256,11
17	15	3,15	9,9225	31,255	98,456	310,136	976,92	47,25	148,837	468,838
18	250	3,7	13,69	50,653	187,41	693,439	2565,7	925	3422,5	12663,2
∑	1794	39,813	97,885	257,57	715,70	2085,90	6339,1	4715	12978,5	37314,1

Table 5. Variance values for the cubic regression function

№	y	$(y-\bar{y})$	$(y-\bar{y})^2$	$Q(L)$	$(Q(L)-\bar{y})$	$(Q(L)-\bar{y})^2$
1	3	-96,6667	9344,444	5,509286	-94,1574	8865,612
2	7	-92,6667	8587,111	0,91844	-98,7482	9751,212
3	120	20,33333	413,4444	50,60951	-49,0572	2406,605
4	20	-79,6667	6346,778	51,61598	-48,0507	2308,869
5	15	-84,6667	7168,444	55,38755	-44,2791	1960,64
6	60	-39,6667	1573,444	66,99181	-32,6749	1067,646
7	16	-83,6667	7000,111	72,75699	-26,9097	724,1308
8	80	-19,6667	386,7778	82,40403	-17,2626	297,9986
9	8	-91,6667	8402,778	82,51599	-17,1507	294,1458
10	150	50,33333	2533,444	93,683	-5,98367	35,80427
11	165	65,33333	4268,444	107,8897	8,223039	67,61837
12	110	10,33333	106,7778	116,3798	16,71317	279,3302
13	210	110,3333	12173,44	138,1271	38,46039	1479,202
14	235	135,3333	18315,11	143,7534	44,08674	1943,641
15	120	20,33333	413,4444	149,0452	49,37849	2438,235
16	210	110,3333	12173,44	184,4693	84,80266	7191,492
17	15	-84,6667	7168,444	187,933	88,26638	7790,954
18	250	150,3333	22600,11	204,994	105,3273	11093,84
$n=18$	$\sum y = 1794$	$\sum(y-\bar{y})^2 = 128976$		$\sum(Q(L)-\bar{y})^2 = 59996{,}97$		
$\bar{y} = \sum y/n =$ 99,67		$\sum(y-\bar{y})^2/n = 7165{,}33$		$\sum(Q(L)-\bar{y})^2/n = 3333{,}16$		

Fig. 4 shows the graphs on which the dependences of regressions was compare with the studied parameters of departure and carrying capacity for industrial manipulators.

CONCLUSION

The conducted research made it possible to determine the analytical dependences for the parameters of load capacity and reach of industrial manipulators of spherical layout.

Fig 4. Graphics for comparison

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Дослідження взаємозв'язків між технічними параметрами промислових маніпуляторів

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Анотація. Промислові маніпулятори стали невід'ємною частиною сучасного будівельного виробництва, відіграючи ключову роль в автоматизації та оптимізації виробничих процесів. При проектуванні та використанні промислових маніпуляторів важливо знати різні параметри, які взаємодіють між собою та впливають на загальну продуктивність і ефективність виробничої лінії в якій працюють промислові маніпулятори. При проектуванні роботизованих процесів будівельного виробництва необхідно точно знати технічні вимоги, які необхідно забезпечувати роботизованими системами. Тому при конструюванні промислових роботів та маніпуляторів необхідно враховувати форму, габаритні розміри та масу будівельних конструкцій з якими буде працювати промисловий робот, а також їхні фізико-механічні властивості. Ці параметри будуть визначати загальну схему та компонування вузлів робота, конструкцію затискного пристрою та зусилля затискання, тип приводу та принцип його керування. Дана робота присвячена виявленню закономірностей між основними технічними параметрами досяжності та вантажопідйомності промислових маніпуляторів загального призначення закордонного виробництва. Застосовано регресійних аналіз із застосування гіперболічного та кубічного сплайнів. Розв'язок рівнянь регресії виконано на основі мінімізації загального квадратичного відхилення функції кореляції.

Результати роботи будуть корисними для розробників промислових роботів та дослідників, які займаються розробкою роботизованих технологічних ліній та виробництв.

Ключові слова: параметри маніпуляторів, взаємозв'язки між параметрами, промислові маніпулятори, теорія кореляції, метод найменших квадратів.