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Kolesnichenko Ruslan Vladislavovich — teaching assistant of the Department «Robotics and mechatronics» of MSUT «STANKIN».

E-mail: ruslanrobotic@gmail.com

Feasibility analysis of construction of precision technological robots on dual-motor geared servo drives

The article presents the results of analysis, which confirm feasibility of construction of precision technological robots on dual-motor geared servo drives, in which mechanical gears are included into position control loop of the control object. The results of the research show that their usage provides improvement of weight, size, energy and cost indicators of technological robots in comparison with such indicators of the robots, built on gearless drives and geared drives with traditional structure.

Key words: robot, manipulator, gearless drive, direct drive, dual-motor drive, high accuracy.

Introduction

The modern stage of technological robotics is characterized by toughening of the requirements to movement accuracy of robots' effectors while performing operations such as laser cutting and welding, plasma processing and dimensional mechanical processing of products with complex shapes of surfaces, when implementation of analytical programming is required. However, a lot of commercially available universal technological robots have drives that do not provide sufficient accuracy of movements in order to implement the above-mentioned operations [1, 2]. Therefore, there is an urgent task to improve structures and control methods of the drives of technological robots.

Usually geared servo drives with traditional structure are used in such robots. The main feedback control loop in these drives is closed by position control loop of the motor shaft, and gears are beyond the position control loop. According to some theoretical and experimental research, for example, [1, 2], such solution provides working capacity of drives and allows us to exclude self-oscillations. However, accuracy of the robot in this case is significantly reduced, since the inherent backlash and elasticity of the gearboxes lead to significant deviations of the robot's end effector from the desired position. At the same time, it is impossible to increase the accuracy of robot movements by including mechanical gears in position control loops without significant changes in the structure of control systems and introduction of additional force elements in the drives, as shown in [1].

Servo drives, closed by position control loop of the manipulator links of technological robots, have higher accuracy. Among such drives are: gearless drives (direct drives) and precision dual-motor geared drives [1, 2, 4, 5]. The peculiarity of the latter is that one motor is a part of the servo drive, which controls the position of the control object, and the other motor is a part of the torque loader, playing the role of an active backlash-eliminating device. Closure of the main feedback loop of the position of the control object, realized by means of a precision position sensor of the manipulator link, leads to significant increase in accuracy and rigidity of the drive and the entire manipulator.

Various structures of dual-motor drives can be found in [6, 7, 8]. However, the structure under consideration differs in that it allows simultaneously excluding limit cycles and, due to the introduction of corrective velocity feedback loop of the manipulator link, carrying out the necessary damping of oscillations, as shown in [3], thus ensuring high accuracy.

As a result of the conducted research, energy, cost and mass-size parameters of manipulators of technological robots, which can be built on gearless and precision dual-motor geared servo drives, have been determined. These assessments of the parameters serve as a basis for making a decision on the feasibility of using such types of drives in technological robotics.

1. Selection of robot manipulation mechanism for comparing characteristics of the drives

The characteristics of the manipulation mechanism affect the requirements to the drives and the energy, mass, size and cost parameters of the robot as a whole. Since laser cutting and welding, plasma machining and dimensional machining most often require manipulation mechanisms with an open kinematic chain and with a large working area, an anthropomorphic manipulator with six degrees of freedom was considered in the study (Figure 1).

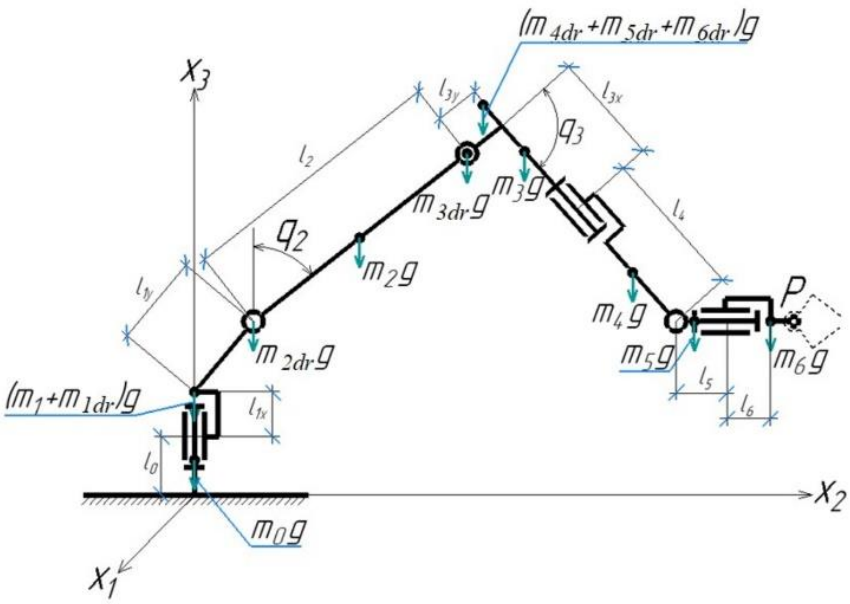

Fig. 1. Kinematic diagram of the manipulator

The manipulators load capacity was assumed to be 16 kg. The parameters m_{1dr}, …, m_{6dr}, shown in Figure 1, represent the masses of the drives. The values of lengths l_0, l_{1x}, l_{1y}, l_2, l_{3x}, l_{3y}, l_4, l_5, l_6 and masses m_0, m_1, m_2, m_3, m_4, m_5, m_6 of the links are presented in the Table 1.

Table 1 - Mass and dimensional parameters of the manipulator links

	manipulator base	**manipulator links**					
		column	**shoulder**	**elbow**	**fourth**	**fifth**	**sixth**
Weight, kg	$m_0 = 53$	$m_1 = 39.7$	$m_2 = 24.3$	$m_3 = 22.2$	$m_4 = 5.6$	$m_5 = 4.5$	$m_6 = 0.2$
Length, m	$l_0 = 0.39$	l_{1x}=0.26 l_{1y}=0.285	$l_2 = 0715$	l_{3x}=0.26 l_{3y}=0.035	$l_4 = 0.18$	l_5=0.15	l_6=0.01

For the research the drives only in its major axes were considered, since they are the main contributors to the formation of estimates of the mass-size and cost indicators of the robot. Estimates of mass and cost of the manipulation mechanism are presented in Table 2.

Table 2 - Cost and mass estimates of the manipulator

Parameter	**Value**
$\sum M_{robot\_without\_drives}$, mass of the robot without drives in major axes, kg	166
M_{robot}, robot mass, kg	235
$P_{robot\_without\_drives}$, cost of the robot without drives in major axes, €	39 448
P_{robot}, cost of the robot, €	57 486

The requirements to the rated torque, speed and power of the elbow link drive of the manipulator are summarized in Table 3. It was taken into account that the rotation of the elbow link should occur at a maximum speed of 2.72 rad/s.

Table 3 - Requirements to the power characteristics of the drives in the manipulator's major axes

	manipulator column	**Shoulder link**	**Elbow link**
M, N*m	1150	1150	438.2
ω, rad/s	26	26	26
W, W	3132	3132	1193

2. **Selection of motors and gearboxes for dual-motor drives in major manipulator axes**

The most frequently used in modern robotics and widely produced by the industry PMSM motors were considered for the usage in dual-motor drives, both as a part of internal servo drives [4] and as a part of torque loaders. As loaders in such drives it is reasonable to use the same models of motors and gearboxes as in internal servo drives, as it provides elimination of backlash and elastic deformations regardless of the direction of action of external forces, applied to the manipulator link.

After that the permissible gear ratios of the gearboxes were determined and various models of the gears were selected. It was assumed that they should be sufficiently accurate, and the error caused by their backlash should be within 1 angular minute. It was also necessary that the rated speed and torque values of the selected gearboxes were greater than the previously calculated required values, and that the combined motor and gearbox moment of inertia matched the maximum load. Since the load with moderate shocks is assumed in the industrial robot, the following condition must be fulfilled with known values of the moment of inertia of the manipulator link, the moment of inertia of the gearbox and its gear ratio:

$$1 < \frac{J_{\text{нагр}}}{J_{\text{р}} * {i_{\text{ред}}}^2} \leq 3$$

The following requirements were also met when selecting motors and gearboxes:

- The drive must have minimum mass and dimensions.
- The drive must have a minimum cost.
- The diameter of the gearbox mounting bore should match the diameter of the motor output shaft in order to ease the installation.
- It is desirable that the gearbox has a flange instead of an output shaft on which the manipulator link can be mounted.

Taking into account these conditions, 5 motors and 5 gearboxes from different manufacturers were selected, first for the dual-motor drive of the elbow link of the manipulator. The arithmetic mean value of the total mass of the elbow link drive was determined and the required torques and angular velocities for the drives of column and shoulder links with the installed dual-motor drive in the elbow link were calculated. These values were then used to select motors and gearboxes for the drives of column and shoulder links of the manipulator.

The required values of energy parameters are presented in Table 4. According to these values the selection of motors and gearboxes of drives of all major axes of the manipulators was carried out. Power requirements to the drives of the column and shoulder link are the same, as the maximum values of the moments of inertia of the control objects of these drives are practically the same and are achieved when the manipulator is pulled out, when the tool center point is maximally distant from its base.

In this way the motors and gearboxes of the drive of the elbow link, which parameters are presented in Table 5, and the drives of the column and shoulder links, which parameters are presented in Table 6, are selected sequentially. The data on the cost of motors and gearboxes presented in the tables are obtained from various supplier firms operating in the city of Moscow, Russia in February - March 2018.

Table 4 - Energy parameters of dual-motor drives in major manipulator axes

	Manipulator column	**Shoulder link**	**Elbow link**
M, N*m	1150	1150	438.2
ω, rad/s	26	26	26
W, W	3132	3132	1193

Table 5 - Motors and gearboxes of the dual-motor drive of the elbow link

№	**U_{nom}, V**	**A_{nom}, A**	**n_{nom}, rpm**	**M_{nom}, N*m**	**W, W**	**J_{mot}, kg*m^2**	**m, kg**	**S_l, mm**	**S_w, mm**	**P, €**
Motors of the elbow linkage drive										
1	Siemens 1FK7060-5AF71-1EB5									
	600	3.7	3000	4.7	1476.5	$7.7 \cdot 10^{-4}$	8.302	200	126	1793.8
2	KEB C4.SM.001-320F									
	230	7.1	3000	5	1476.5	$5.4 \cdot 10^{-4}$	6.6	294	92	2220.8
3	Kollmorgen AKM43L-ANC22-004572									
	240	11.2	6000	4.73	1590	$2.16 \cdot 10^{-4}$	4.98	210.3	100	1975.1
4	Bosch Rexroth MS2N05-C0BNN-CSDL1-NNANN-NN									
	600	3.55	3000	6.1	1916.4	$4 \cdot 10^{-4}$	7	254	98	1096
5	Mitsubishi HG-JR153BWDC									
	200	11	3000	4.8	1508	$4.3 \cdot 10^{-4}$	7.3	245	90	1949.4

№	**i_{gear}**	**n_{nom}, rpm**	**M_{nom}, N*m**	**C_{gear}, N*m/rad**	**J_{gear}, kg*m^2**	**m, kg**	**S_l, mm**	**S_w, mm**	**P, €**
Gearboxes of the elbow linkage drive									
1	Spinea TS170-125-E-P19-0589 A with flange for motor mounting								
	125	2000	495	378152	$1.15 \cdot 10^{-4}$	10.8	93	190	3729
2	Harmonic Drive HFUC-50-2UH 120 (oil lubrication) can be used with Siemens 1FK7060-5AF71-1EB5 motor according to the requirement to moment of inertia; a housing with bearings and space for the motor is required								
	120	3000	529	440000	$12.6 \cdot 10^{-4}$	8.9	90	190	6209.15
3	Wittenstein TP 050S-MA3-110-0G1 with space for motor installation								
	110	3500	675	44690	$2.2 \cdot 10^{-4}$	13.4	206	179	3904
4	Fyne Cyclo FC-A35G i=119 with adapter for motor mounting								
	119	2975	544	110000	$4.58 \cdot 10^{-4}$	9.6	85	180	1710
5	Nabtesco RV-60 i=121 a housing with bearings and space for the motor is required								
	121	6050	547	196000	$0.328 \cdot 10^{-4}$	10	71.5	200	1719

Table 6 - Motors and gearboxes of dual-motor drives of robots’ column and shoulder links

№	U_{nom}, V	A_{nom}, A	n_{nom}, rpm	M_{nom}, N*m	W, W	J_{mot}, kg*m^2	m, kg	S_l, mm	S_w, mm	P, €
Motors of the column and shoulder linkage drives										
1	Siemens 1FK7083-2AF74-1EB1									
	600	7.4	3000	10.5	3298.7	$26 \cdot 10^{-4}$	15.9	266	130	1930.4
2	KEB D4.SM.001-420F									
	230	18.2	4000	12	3602.4	$12.7 \cdot 10^{-4}$	11.2	315	110	2848
3	Kollmorgen AKM52L-ANC22-00									
	240	11.6	3500	8.7	3177.7	$6.37 \cdot 10^{-4}$	6.9	203.5	130	1979.9
4	Bosch Rexroth MS2N06-D1BNN-CSUL2-NNANN-NN									
	600	4.9	3000	9	2827.4	$15.4 \cdot 10^{-4}$	10.5	254	261	1241
5	Mitsubishi HG-JR353BWDC									
	200	17	3000	10.5	3298.7	$13.2 \cdot 10^{-4}$	13	228	130	2534.9
Gearboxes of the column and shoulder linkage drives										
№	i_{gear}	n_{nom}, rpm	M_{nom}, N*m	C_{gear}, N*m/rad	J_{gear}, kg*m^2	m, kg	S_l, mm	S_w, mm	P, €	
1	Spinea TS220-125-E-P28-0585 with flange for motor mounting									
	125	2000	1250	1065702	$4.8 \cdot 10^{-4}$	22.4	131.5	238	4327.4	
2	Harmonic Drive HFUC-65-2UH 120 (oil lubrication) a housing with bearings and space for the motor is required									
	120	2400	951	980000	$46.8 \cdot 10^{-4}$	20.9	115	260	8244.9	
3	Wittenstein TP 110S-MA3-110-0K1 with space for motor installation									
	110	3000	1750	4992000	$9.8 \cdot 10^{-4}$	35.4	258.4	247	5598	
4	Fine Cyclo F2C(F)-T455 i=118.5 requires a housing for the motor installation									
	118.5	2962	1090	732200	$1.92 \cdot 10^{-4}$	24	113	230	4265	
5	Nabtesco RV-160 i=129 a housing with bearings and space for the motor is required									
	129	3225	1343	1348000	$1.1 \cdot 10^{-4}$	20	96	239.9	2370	

3. Selection of motors for gearless drives in major manipulator axes

For gearless drives brushless high-torque motors were considered. The required values of velocity and torque developed by gearless drives of the manipulator were calculated using the same methodology as for dual-motor drives. Firstly 5 motors of the gearless drive of the elbow link were selected. Then, taking into account their arithmetic mean mass, the values of the required velocity and torque of the drives of the column and shoulder links were calculated, and 5 motors for these drives were selected. The calculated values are presented in Table 7. Parameters of the selected motors for the elbow link drive are presented in Table 8, for shoulder link and column – in Table 9.

Table 7 - Energy parameters of gearless manipulator drives

	Manipulator column	**Shoulder link**	**Elbow link**
M, Н*м	1160	1160	438.2
ω, рад/с	26	26	26
W, Вт	3159	3159	1193

It should be noted that a significant disadvantage of gearless drives is the need to provide a coolant supply to obtain the required high energy characteristics. Such a supply is particularly difficult on a manipulator, which limits the application of such drives in robotics. Also, the choice of motors for gearless actuators is currently not as large. In the power range under consideration, the choice is very limited, as the industry mainly uses more dynamic drives with lower rated torque and higher speeds. This makes it necessary to select higher power motors capable of delivering the required torque, and this results in a certain redundancy.

Table 8 - Motors for gearless drives of the elbow link

№	U_{nom}, V	A_{nom}, A	n_{nom}, rpm	M_{nom}, N*m	W, W	J_{mot}, kg*m^2	m, kg	S_l, mm	S_w, mm	P, €
Motors of the elbow linkage drive										
1	Siemens 1FW6160-0TB07-1JC2 coolant supply, US patent US5584621 for use in robot joints, bearings, encoder, brake required									
	600	18	594	170	10574.6	0.258	48.3	130	440	9703.8
2	Etel TMB+0360-070 TF coolant supply, housing, bearings, encoder, brake required									
	600	56.7	596	26	1622	0.152	39.9	130	365	don't sell to Russia
3	Kollmorgen KBMS-88H03-C housing, bearings, encoder, brake required									
	400	45.2	545	425	24255.7	0.315	11	270.8	331.5	22625.88
4	Bosch Rexroth MST290E-0004-FH-N0PU-NNNN (stator) and MRT290E-3N-0200-NNNN (rotor) coolant supply, housing, bearings, encoder, brake required									
	540	12.5	575	40	2408.5	0.17	36.7	195	310	7584
5	Alxion 500STK2M 2C010HA coolant supply, housing, bearings, encoder, brake required									
	400	14.8	588	50	3078.8	0.433	43	120.5	502	5260

Table 9 - Motors for gearless drives of column and shoulder links

№	U_{nom}, V	A_{nom}, A	n_{nom}, rpm	M_{nom}, N*m	W, W	J_{mot}, kg*m^2	m, kg	S_l, mm	S_w, mm	P, €
Motors of the column and shoulder linkage drives										
1	Siemens 1FW6190-0TB10-2JC2 10 bar coolant supply, US patent US5584621 for use in robot articulations, bearings, encoder, brake required									
	600	30	1290	70	9456	0.678	75.8	160	502	14065.2
2	Etel TMB0360-150 3UFN coolant supply, housing, bearings, encoder, brake required									
	300	72.7	1240	26	3376.5	0.327	70.9	210	385	don't sell to Russia
3	Kollmorgen KBMS-163H02-A requires housing, bearings, encoder, brake									
	400	39.5	1090	200	22828.9	1.72	136	193.3	537.2	37420.3
4	Bosch Rexroth MST450E-0006-FH-N0KR-NNNN (stator) and MRT450E-3N-0350-NNNN (rotor) coolant supply, housing, bearings, encoder, brake required									
	540	32	1400	60	8796.5	1.01	81.9	210	480	9990
5	Alxion 500STK3M 3C010HA coolant supply, housing, bearings, encoder, brake required									
	400	30.7	1180	50	6178.5	0.649	58	148	502	6900

4 Determination of the mass-size and cost indicators of the manipulator with the selected drives

The comparison of the characteristics of manipulators of technological robots built on the considered types of drives was carried out on the basis of the arithmetic mean values of mass-size and cost indicators of manipulators with these drives. At the same time the values of mass $\boldsymbol{m}$ and cost $\boldsymbol{P}$ of the selected drives, as long as the volume of space $\boldsymbol{V}_{\Sigma}$, occupied by them, were determined. The volume of motors was defined as the volume of a parallelepiped shape, and the volume of gearboxes was defined as the volume of a cylindrical shape, using arithmetic mean values of length and width of the selected motors and gearboxes. The volume of gearless drives was also defined as the volume of a cylinder-shaped figure. As a result, the data presented in Table 10 were obtained, where $\boldsymbol{V}_{mot}$ is the volume of space occupied by the motor of the dual-motor drive, $\boldsymbol{V}_{red}$ is the volume of space occupied by its gearbox.

Table 10 - Comparison of mass-size and cost indicators of dual-motor and gearless drives of carrying links of manipulator

Drive type	**elbow link drive**					**column and shoulder link drives**				
	m, kg	V_{mot}, mm^3	V_{red}, mm^3	V_{Σ}, mm^3	P, €	m, kg	V_{mot}, mm^3	V_{red}, mm^3	V_{Σ}, mm^3	P, €
Dual-motor	35	$2.47 \cdot 10^{-3}$	$3.02 \cdot 10^{-3}$	0.011	9.2	72	$5.87 \cdot 10^{-3}$	$6.62 \cdot 10^{-3}$	0.025	14.1
Gearless	36	-		0.02	11.3	85	-		0.034	17.1

According to the presented data, it can be seen that the selected dual-motor drives have lower values of mass, size and cost parameters compared to gearless drives. Such manipulator parameters as the total robot mass $\sum M$, its cost $\sum P$, as well as the space occupied by the drives in major axes $\sum V_{ma}$ are obtained. The obtained values are presented in Table 11.

Table 11 - Comparison of mass-size and cost indicators of manipulators built on single-motor, dual-motor and gearless drives in major axes

Evaluation criterion	**Type of drives in major manipulator axes**		
	Single-motor	Dual-motor	Gearless
$\sum M$, kg	235	344	371
mass change factor	1	1.5	1.6
$\sum V_{ma}$, m^3	0.018	0.061	0.087
drive volume change factor	1	3.4	4.9
$\sum P$, thsd. €	57.5	76.9	84.9
cost change factor	1	1.3	1.5

Table 11 also presents the coefficients of relative change in the volume of drives in major axes, as well as the mass and cost of the manipulator, which show how many times a particular parameter will change if the manipulator is built on single-motor drives, on dual-motor or gearless drives. As can be seen, for all three parameters, the coefficient of variation for the manipulator with dual-motor drives is smaller than for the manipulator with gearless drives.

Thus, the presented results of the analysis indicate that in major axes of manipulators of technological robots, which must have increased accuracy of movements, the usage of precision dual-motor geared drives is more favorable than the usage of gearless drives.

Conclusions

On the one hand, the usage of precision drives increases the mass and cost of the robot arm compared to the case of traditional geared drives. However, this is a justified price to pay for a significant increase in accuracy of movements realized by the robot. At the same time, the influence of different types of precision drives on the manipulator characteristics is different.

According to the results of the research, the usage of precision dual-motor geared drives and gearless drives only in major axes leads to increase in cost of the manipulator on average by 33.7 % and 47.7 %, respectively. And the weight increase of the manipulator with the usage of precision dual-motor geared drives and gearless drives on average is 46.6 % and 57.8 % respectively. At the same time, the presented results do not yet take into account the masses of coolant supply devices and additional accessories (rotor bearings, encoder, brake) for gearless drives, which would lead to an even greater increase in the mass and cost estimates of the manipulator.

As a result, from the point of view of minimizing the cost and mass of the manipulator for building high-precision technological robots, it is more appropriate to use precision dual-motor geared drives than gearless drives. In this case, it is possible to increase the allowable contour speed and productivity of technological robots, as shown in [9, 10], which contributes to the expansion of their application area and improvement of their efficiency.

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