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Accuracy Investigations of Multifunctional Two-coordinate Drive System

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Introduction

Every specific task for two-coordinate drive system such as positioning or scanning requires specific control algorithm. The multifunctional control system proposed in [7, 9] enables to control several problems leaving the hardware of two-coordinate drive system unmodified. These control methods are represented in detail in [6,8,10]. In this article there is analyzed one of the most important characteristics of this kind of systems – position absolute and repetition accuracy. The influence of control methods that ensure optimum rapidity and increase long life of the system and power efficiency on position repetition accuracy is evaluated. The main purpose of this article is to show the investigation technique and results on position accuracy of multifunctional two-coordinate drive system.

The reminder of this article has been organized in such order. In section 2, there is given the discussion on different positioning and scanning modes in two-dimensional space. The main notice is pointed to the mode, which is optimal in respect to cycle time and optimization of mechanical actions to the mechanical part of the system and power consumption. The investigation technique of position absolute and repetition accuracy of two-coordinate drive system is shown in section 3. Section 4 illustrates the framework for experiments with industrial drives. The experimental and estimation results on absolute and repetition accuracy of multifunctional two-coordinate drive system are given in section 5. Finally, conclusions are presented in section 6.

Discussion on functioning modes of multifunctional two-coordinate drive system

Positioning mode. Various trajectories of two-coordinate positioning system represent its control algorithm, functioning mode and efficiency. Fig. 1 represents three different trajectories, when multifunctional two-coordinate drive system acts in positioning mode.

Positioning systems acting in sequential order are used for non-complicated cyclic processes. In this case every drive makes its move with the referred displacement after each another. This sequential trajectory is shown in Fig. 1a. The control algorithm representing this trajectory is related with maximal time costs. Therefore, the total positioning time of two-coordinate drive system is equal:

$$t_p = t_{p1} + t_{p2}; \tag{1}$$

where t_{p1} – positioning time in the first direction, t_{p2} – positioning time in the second direction.

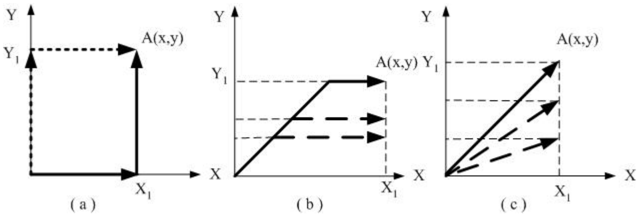

Fig. 1. Trajectories of two-coordinate positioning system

With purpose to minimize positioning cycles of two-coordinate system the independent drives are equipped for both coordinates. In this case control system becomes also simple and positioning trajectory is not being controlled. The maximum rapidity of two-coordinate drive system is obtained by the means of maximum rapidity mode, in which both drives act. The positioning trajectory of this control algorithm is represented in Fig. 1b. When both positioning drives act with the same rapidity, the total positioning time is equal to the time, which is needed for the drive with larger referred displacement to reach target:

$$t_p = t_{p1}. \tag{2}$$

In this case both positioning drives acts with maximal dynamic torques and the positioning process needs more energy resources.

For minimization of power losses the control algorithm, which assures linear positioning trajectory, should be used.

Harmonization of two-coordinate positioning drives realizes such control strategy, which ensures optimum rapidity of object transportation in the two-dimensional space and allows saving of power and equipment resources. The coordination of movements of two-coordinate positioning system is realized in such way that the bigger displacement performing (master) drive acts under the optimum rapidity condition and other smaller displacement performing (slave) drive ensures the linearity of positioning trajectory. In this case the positioning process in the smaller displacement direction takes place with diminished forces and equipment wear, and is performed at the same time as the bigger displacement. When multifunctional two-coordinate drive system acts in such mode, the total positioning time is equal:

$$t_p = t_{p1} = t_{p2}. \tag{3}$$

From equations (2) and (3) it could be seen that both control regimes, described by Fig. 1b, Fig. 1c, are optimal regarding the cycle time.

The positioning trajectory of the control algorithm, which realizes the minimization of power losses, is represented in Fig. 1c. The control algorithm, which enables possibility to increase durability of device and decrease power consumption, was presented in detail in [5].

The main requirements that are being raised for industrial positioning systems are positioning cycles and absolute and repetition accuracy. As it was already mentioned, the positioning cycle is defined by rapidity of positioning system. The accuracy is being influenced by quality of control system and all mechanical parts of the positioning system.

After discussion on three different trajectories of two-coordinate positioning system we can conclude that control method insuring linear positioning trajectory is optimal in respect to the process cycle and optimizes mechanical actions to the mechanical part of the system and power consumption.

Scanning mode. When multifunctional two-coordinate drive system is switched on to the scanning mode, there could also be several regimes, defined by different scanning trajectories. Possible trajectories of scanning process are shown in Fig. 2. Picture in Fig. 2a represents scanning process, where two drives act in sequential order. This control algorithm is non-optimal in respect of cycle time. In this case the total scanning time is equal:

$$t_p = \sum_{i=1}^{n} (t_{Xi} + t_{Yi}); \tag{4}$$

where t_{Xi} - travel time of shuttle drive in X direction, t_{Yi} - travel time of step drive in Y direction.

Picture in Fig. 2b represents scanning process, where motions of two acting drives are co-coordinately controlled. This control algorithm is optimal in respect to cycle time of equipment, because the total time of scanning process is defined:

$$t_p = \sum_{i=1}^{n} t_{Xi}. \tag{5}$$

In this case total time is influenced by cycle of acting shuttle drive; step drive moves during the reverse movement of shuttle drive.

The stepping drive is designed and controlled in such a way, that it doesn't decrease the productivity of the scanning process and it is able to make a step of appointed size during the reverse time of the shuttle drive. Therefore, the maximum possible scanning process productivity assurance is the main task, which must be realized by the scanning device control system.

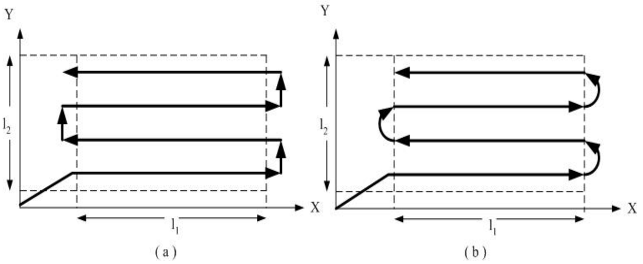

Fig. 2. Trajectories of two-coordinate scanning system

The other task, which is to be realized by control system, is the optimization of mechanical actions to the mechanical part of the system (the long life of the system increasing) and optimization of power consumption (the power efficiency increasing) [7].

From equations (4), (5) and discussions on control regimes for scanning process, it can be concluded that control method, described by trajectory in Fig. 2b, is optimal in respect to cycle time, durability and power consumption of device.

Approach of investigation of absolute and repetition accuracy of two-coordinate drive system

Two-coordinate drive systems designed for handling applications, planar manipulators, positioning of the two-coordinate tables, co-ordination of movements of scanning devices and in many other cases, the most important characteristic data is position repetition accuracy.

We have to be sure that proposed control methods for the two-coordinate positioning and scanning system (optimizing of mechanical actions to the mechanical part of the system and power consumption) insure position absolute and repetition accuracy, which is not apparently larger than accuracy of two-coordinate drive system controlled by ordinary (let's call then "non-optimal") control methods.

While speaking about multifunctional two-coordinate drive system, performing positioning tasks, we have to analyze the accuracy of the system, which are controlled in such a way that the positioning trajectories correspond to those represented in Fig. 1.

In control method that insures the linearity of positioning trajectory the bigger displacement performing (master) drive acts under the optimum rapidity conditions and independently form slave drive, meanwhile smaller displacement performing (slave) drive ensures is controlled according the velocity of master drive. Therefore the largest interest lies in behaviour and accuracy of slave drive. In this case we are going to investigate the accuracy of Y drive acting under different conditions, determined by different trajectories (see Fig. 1).

Analyzing multifunctional two-coordinate drive system in scanning process, we have to compare accuracy of system that is controlled by control methods, conditioned by the trajectories shown in Fig. 2.

In this case we confine research of repetition accuracy of two-coordinate scanning system. We are interested only in behaviour of stepper drive, which acts in Y direction (see Fig. 2). Here we assume that accuracy of shuttle drive is the same in both control regimes, because this drive always acts independently.

The position repetition accuracy defines the acceptable variation range for numerous approaches to a certain position value. The actual positions approached vary by a statistical expectation from the absolute position deviation (absolute accuracy) relative to a set-point position. For this purpose, the determined position deviation (= actual position value – set-point) of several positioning operations is evaluated statistically.

At the given process conditions like velocity, acceleration and deceleration of drive measured position value of the drive is described by X_{ij}, where i – number of observation results values, j – set-point position number (i.e. 1 – set-point position $X = X_1$ mm, 2 – set-point position $X = X_2$ mm and etc.). The mean value of X_j sets can be found:

$$\overline{X} = \overline{X}_j = \frac{1}{n}\sum_{i=1}^{n} X_{ij}, \tag{6}$$

where n – the maximum number of observation results values.

Standard deviation, which is equal:

$$\sigma_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\overline{X}_j - X_{ij})^2}. \tag{7}$$

Value σ characterizes the standard deviation of one series of measurements at one set-point value.

After we find all the σ_j values of sets of measurements at the different set-point values, the total standard deviation could be found:

$$\sigma = MAX\{\sigma_j\}. \tag{8}$$

With reference to (8) equality the repetition accuracy of system is defined as twice the standard deviation $\pm 2\sigma$. This means that 95.4% of all positioning operations to the defined set-point position X_{sp} will lie within the range of $\overline{X} \pm 2\sigma$.

In contrast to repetition accuracy, absolute accuracy can be defined as the deviation of arithmetical mean of all position values of a series of measurements from set-point position, i.e. $\left|\overline{X}_j - X_{sp}\right|$.

Experiments

Two-coordinate industrial drive system, consisting of identical drives, was used as framework for experiments. Schematic of experimental base is shown in Fig. 3. The main parts of this system are servo controller SEC-AC with integrated controller and power unit functions, AC brushless servomotors of MTR-AC-70-3S-AA type and toothed belt axes of DGE-25-500-ZR-… type (diameter of drive – 25 mm, working stroke – 500 mm, feed constant – 63 mm/rotation). SEC-AC has such a structure where current controller, speed controller and positioning module are arranged in form of cascade control.

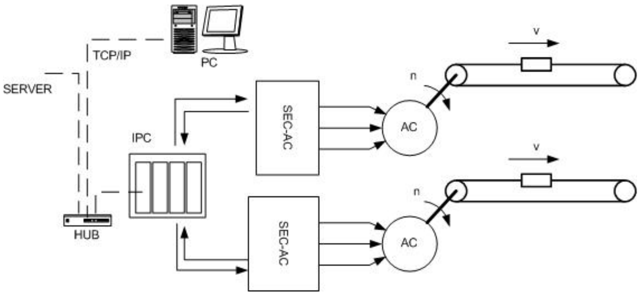

Fig. 3. Schematics of experimental base

Due to the rotor-orientated control principle, the current can be specified separately in the effective share and the idle share. Therefore there are two current controllers, each of which has been designed as a PI controller. The speed controller and positioning module have also been designed as PI controller and can be switch on/off individually. For realization of control methods, discussed in chapter 2, the servo controller was switched to speed-control mode. Further more industrial personal computer (IPC) with analogue inputs/outputs was used for specifying the set-point signals for servo drives and receiving feedback signals. DDE server program was used for data acquisition from industrial personal computer. For this case TCP/IP driver was installed in IPC. It enabled communications between IPC and PC. DDE server program acquired data, which later was used for estimations.

There were made several experiments with the purpose to assign the absolute and repetition accuracy of drives, control by different control methods.

Positioning process. The experimental conditions for multifunctional two-coordinate drive system, acting in positioning mode, were: maximum velocity for both drives $v_{max} = 0.95$ m/s, acceleration $a = 4.7$ m/s^2. Measurements were carried out at the different set-point values: 1) $X_1 = 378$ mm, $Y_1 = 315$ mm; 2) $X_2 = 378$ mm, $Y_2 = 150$ mm; 3) $X_3 = 378$ mm, $Y_3 = 30$ mm. Number of observation results values $n = 100$. The increments of resolver of servomotor were used as the observation results values. The relationship between the resolver increments and linear path of toothed belt drive is equal: 1 inc = 0.01575 mm.

Since we don't concentrate on the measuring accuracy but on the comparison of absolute and repetition accuracy of two-coordinate system in different modes, we assume that such measuring technique and means are sufficient for this purpose.

The experiments were carried out using three different control regimes: 1) when drives act in sequential order (Fig. 1a and Fig. 6); 2) both drives act independently (Fig. 1b and Fig. 5); 3) drives move coordinately controlled (Fig. 1c. and Fig. 4).

In Fig. 4 there is shown the positioning process of two-coordinate drive system, when the bigger displacement (X_1 = 378 mm) performing drive acts independently and the smaller displacement (Y_2 = 150 mm) performing drive is controlled according to the velocity of master drive. From Fig. 4 it could be seen that velocity of slave drive (1) is controlled according the velocity signal of master drive (2).

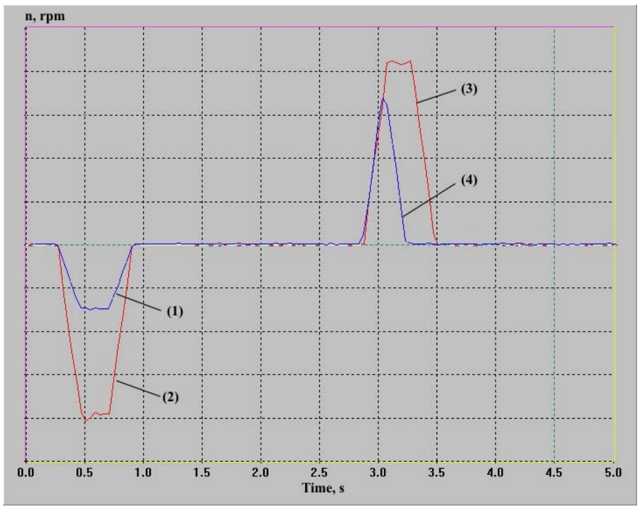

Fig. 4. Velocity signals of master and slave drives while positioning trajectory is linear

In the first period of positioning process drives move in linear trajectory, in the second – they move independently. The curves are indicated in such order: (1) – velocity signal of slave (*Y*) drive in the 1st period, (2) – velocity signal of master (*X*) drive in the 1st period, (3) – velocity signal of master (*X*) drive in the 2nd period, (4) – velocity signal of slave (*Y*) drive in the 2nd period.

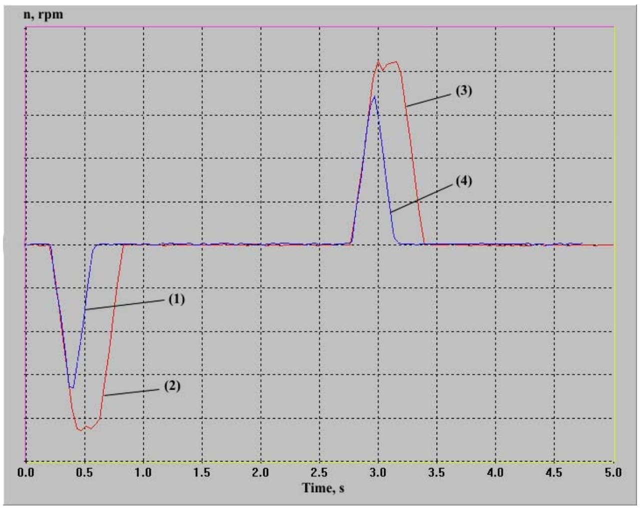

Fig. 5. Velocity signals of two-coordinate positioning system, when both drives act independently

In Fig. 5 there is shown the positioning process of multifunctional two-coordinate drive system, when the bigger displacement (X_1 = 378 mm) performing drive and smaller displacement (Y_2 = 150 mm) performing drive act independently.

In Fig. 6 there is shown the positioning process of two-coordinate drive system, when the bigger displacement (X_1 = 378 mm) performing drive and smaller displacement (Y_2 = 150 mm) performing drive act in sequential order.

In Fig. 5 and 6 the curves are indicated in such order: (1) – velocity signal of the second (*Y*) drive in the 1st period, (2) – velocity signal of the first (*X*) drive in the 1st period, (3) – velocity signal of first (*X*) drive in the 2nd period, (4) – velocity signal of the second (*Y*) drive in the 2nd period.

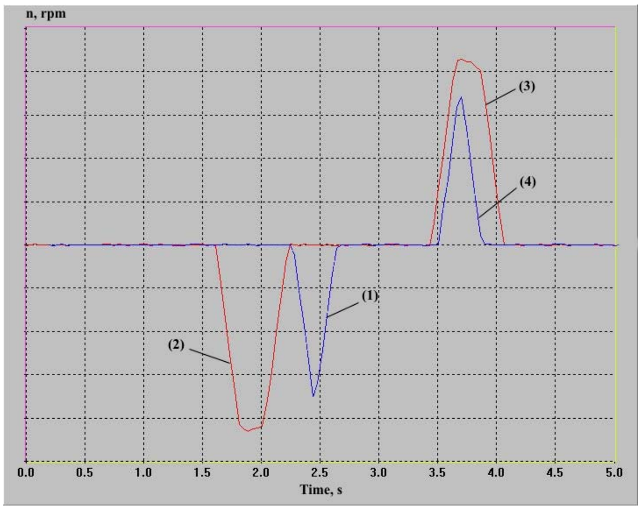

Fig. 6. Velocity signals of two-coordinate positioning system, when drives act in sequential order

In Fig. 4, 5, 6 velocities are displayed in units of rotations per minute (rpm). Scale interval of *y*-axis is equal 100 rpm/div.

Scanning process. The experimental conditions for multifunctional two-coordinate drive system, acting in scanning mode, were: maximum velocity for shuttle drive v_{max} = 0.38 m/s, maximum velocity for stepper drive v_{max} = 0.24 m/s, maximum acceleration of both drives is equal a = 1.57 m/s^2. Measurements were carried out at the different set-point values. The shuttle drive was moving between to points: *A(126, Y_i)* mm and *B(315, Y_i)* mm. The stepper drive moved relatively with defined step size Y_i and number of steps k: 1) Y_1 = 15.75 mm, k = 25; 2) Y_2 = 94.5 mm, k = 4; 3) Y_3 = 189 mm, k = 2. Number of observation results values n = 100.

The experiments were carried out using two different control regimes: 1) when drives act in sequential order (Fig. 2a and Fig. 7); 2) stepper drive makes a step of appointed size during the reverse time of the shuttle drive (Fig. 2b and Fig. 8).

In Fig. 7 and 8 there are shown the scanning processes of two-coordinate drive system, when the stepper drive moves relatively with defined step size respectively Y_1 = 126 mm, number of steps k = 4 and Y_2 = 126 mm, number of steps k = 3. The curves are indicated in such order: (1) – velocity signal of shuttle (*X*) drive, (2) – velocity signal of stepper (*X*) drive.

In Fig. 7, 8 velocities are displayed in units of rotations per minute (rpm). Scale interval of *y*-axis is equal 100 rpm/div.

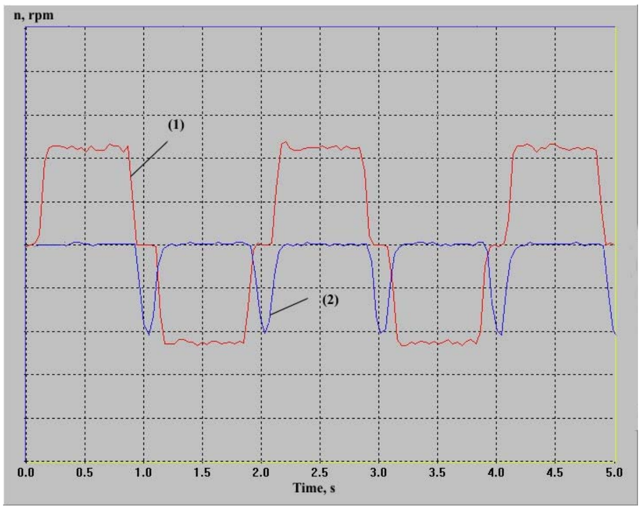

Fig. 7. Velocity signals of two-coordinate scanning system, when drives act in sequential order

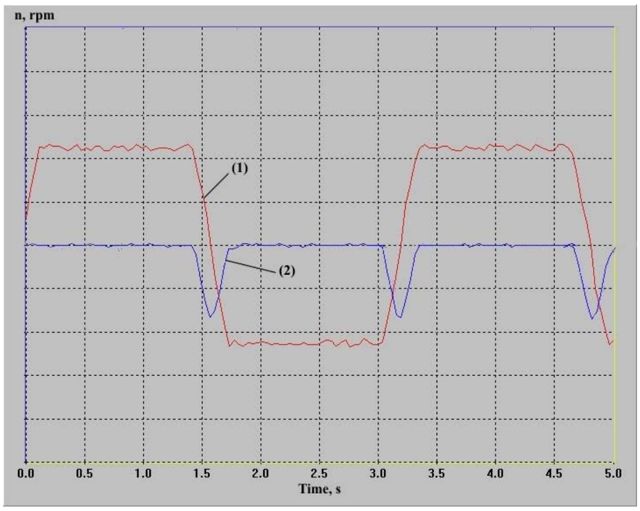

Fig. 8. Velocity signals of two-coordinate scanning system, when stepper drive makes step during the reverse time of shuttle drive

Fig. 8 represents the harmonized control regime, where stepper drive (2) moves during the reverse time of shuttle drive (1).

Results

Estimation of experimental results of two-coordinate positioning system is shown in Table 1. In the first column of table there are represented the set-point values for slave (*Y*) drive at different control methods: * - drives act in sequential order; ** - both drives act independently; *** - the master drive moves independently and the slave drive is controlled according the velocity of master drive. In the second column there are represented mean values of all position values of a series of measurement. Values of standard deviation are listed in the third column. The fourth column represents the absolute accuracy.

When the set-point value for slave drive is equal Y_l = 315 mm, repetition accuracy (±2σ) is the result of 0.0068 mm. This means that 95.4% of all positioning operations to the set-point position 315 mm will lie within the range of 314.9644 mm ± 0.0068 mm. If the repetition accuracy is specified as 3 times the standard deviation (corresponding to 0.0106 mm), 99.78% of all positioning operations will lie in the range of 314.9644 mm ± 0.0106 mm. In this case the absolute accuracy is 0.0356 mm.

Table 1. Estimation of experimental results of two-coordinate positioning system

X_{spj}, mm	$\bar{X}_j, mm$	σ_j, mm	$\lvert X_j - \bar{X}_j \rvert, mm$
30*	29.9939	0.0024	0.0061
150	150.0377	0.0058	0.0377
315	315.0940	0.0088	0.0940
(sequential)	max{}	**0.0088**	**0.0940**
30**	29.9844	0.0034	0.0156
150	150.0389	0.0040	0.0389
315	315.0567	0.0036	0.0567
(independent)	max{}	**0.0040**	**0.0567**
30***	30.0029	0.0041	0.0029
150	150.0330	0.0094	0.0330
315	314.9644	0.0034	0.0356
(coordinated)	max{}	**0.0094**	**0.0356**

Table 2 shows the comparison of standard deviation for different control methods of multifunctional two-coordinate drive system, acting in positioning mode. From results we can see that standard deviations of the system using different control methods are of the same range. From here we can conclude that using control method, which insures linear trajectory positioning process, two-coordinate drive system is not losing position absolute and repetition accuracy. In this case the load and the accuracy degree of the mechanics standing behind the servomotor is not evaluated, the measurements were made using the measuring system of servomotor (resolver).

The last row in table 2 shows the results of the estimation given by toothed belt drives producer. It can be seen that position repetition accuracy approximately is less than 0.2mm. Here the measurements were made at the side of toothed belt drive; the mechanical part and load of 2 kg on drive is taken into account.

Table 2. Comparison of standard deviation (two-coordinate positioning system)

E_j	$\pm\sigma_j, mm$ (68,27%)	$\pm 2\sigma_j, mm$ (95,4%)	$\pm 3\sigma_j, mm$ (99,78%)
$1^{\text{sequential}}$	0.0088	0.0176	0.0264
$2^{\text{independent}}$	0.0040	0.0080	0.0120
$3^{\text{coordinated}}$	0.0094	0.0188	0.0282
$4^{\text{industrial}}$	0.0723	0.1445	0.2168

Fig. 8 shows the histogram, which represents variation range for numerous approaches of slave drive to defined position (*Y* = 30 mm), when multifunctional two-coordinate drive system is being controlled by method, which insures linear positioning trajectory.

Table 3 and 4 represents the estimation results on absolute and repetition accuracy of scanning mode. The first column of table 3 shows relative value of set-point for stepper drive. In the second column absolute values are represented. Further, mean values, deviation and absolute accuracy values are listed.

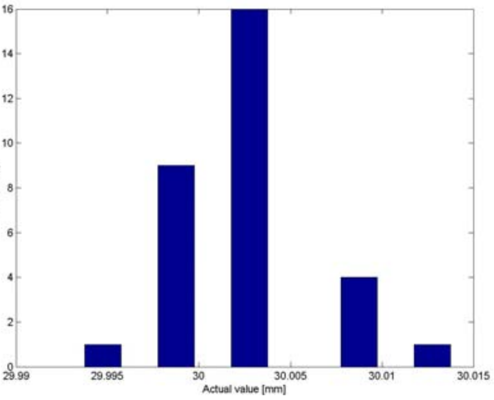

Fig. 9. Variation range for numerous approaches, when set-point position is equal to 30 mm

Table 3. Estimation of experimental results of two-coordinate scanning system

X_{sp}, mm	X_j, mm	$\overline{X}_j$, mm	σ_j, mm	$\lvert X_j - \overline{X}_j \rvert$, mm
15.75*	15.75	15.8086	0.1820	0.0586
	393.75	394.7386	0.1250	0.9886
189**	189	188.9688	0.1266	0.0312
	378	378.2789	0.1057	0.2789
94.5***	94.5	94.3912	0.1271	0.1088
	189	189.0921	0.1298	0.0921
(sequential)		max{}	**0.1820**	**0.9886**
15.75*	315	315.7752	0.1177	0.7752
	378	378.8722	0.1045	0.8722
189**	189	188.8496	0.1142	0.1504
	378	378.2410	0.0955	0.2410
94.5***	94.5	94.3387	0.1189	0.1613
	189	189.0285	0.1099	0.0285
(coordinated)		max{}	**0.1189**	**0.8722**

Because of large amount of measured and calculated experimental data values, there are displayed only several sets of results.

In table set-point values for stepper (*Y*) drive with different step sizes are indicated in such order: * - stepper drive makes k=25 steps with relative move of size s = 15.75 mm; ** - k = 2 and s = 189 mm; *** - k = 4 and s = 94.5 mm.

Fig. 9 shows the histogram, which represents variation range for numerous approaches of stepper drive to defined step size (Y = 15.75 mm), when stepper drive acts during reverse time of shuttle drive.

Table 4. Comparison of standard deviation (two-coordinate positioning system)

E_j	$\pm\sigma_j, mm$ (68,27%)	$\pm 2\sigma_j, mm$ (95,4%)	$\pm 3\sigma_j, mm$ (99,78%)
$1^{\text{sequential}}$	0.1820	0.3640	0.5460
$2^{\text{coordinated}}$	0.1189	0.2378	0.3567

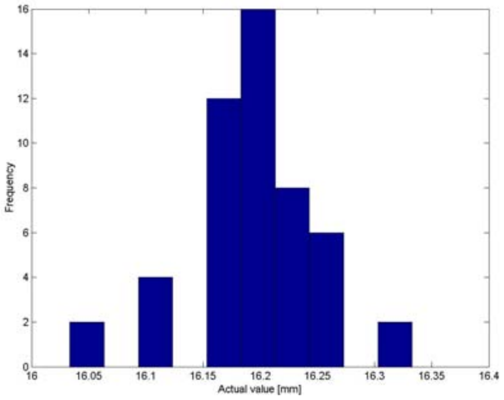

Fig. 10. Variation range for numerous approaches, when step size of stepper drive is equal to 15.75 mm

In common repetition accuracy (±2σ) of multifunctional two-coordinate drive system, which control is conditioned by harmonization of movements of stepper and shuttle drives, is the result of 0.2378 mm.

Conclusions

Appropriate experimental measurements were carried out with the aim to determine the position absolute and repetition accuracy of multifunctional two-coordinate drive system, performing different functions (scanning, positioning) and controlled using various control methods.

From experimental results and statistical evaluations it could be seen that the repetition and absolute accuracy of two-coordinate drive system do not come worse using control methods that ensure optimum rapidity and optimization of mechanical actions to the mechanical part of the system (the long life of the system increasing) and optimization of power consumption (the power efficiency increasing). Therefore, it can be concluded that multifunctionality of two-coordinate drive system doesn't influence the accuracy.

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Analizuojamas vienas iš svarbiausių dvikoordinačių vykdymo sistemų parametrų – pozicionavimo tikslumas. Įvertinama valdymo algoritmų, kurie dvikoordinatei vykdymo sistemai užtikrina optimalią greitaveiką, sistemos ilgaamžiškumą bei sumažina energijos sąnaudas, įtaka pasikartojančiam sistemos tikslumui. Atlikti eksperimentiniai tyrimai su pramoninėmis pavaromis parodo, kad absoliutinis ir pasikartojantis dvikoordinačių sistemų tikslumas nesumažėja, taikant valdymo metodus, įgalinančius optimaliai greičio, ilgaamžiškumo ir energijos sąnaudų atžvilgiu realizuoti tokias specifines užduotis kaip dvimatis pozicionavimas ir skenavimas. Il.10, bibl. 12 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

G. Blažiūnas, V.A. Geleževičius. Accuracy Investigations of Multifunctional Two-coordinate Drive System // Electronics and Electrical Engineering. – Kaunas: Technologija, 2004. – No. 2(51). – P. 8-14.

In this article there is analyzed one of the most important characteristics of two-coordinate drive systems, i.e. position absolute and repetition accuracy. The influence of control methods, that ensure optimum rapidity and increase durability of the system and power efficiency, on position repetition accuracy is evaluated. The experimental measurements were carried out using industrial drives. From experimental results and statistical evaluations it can be concluded that position absolute and repetition accuracy of two-coordinate drive system do not come worse using control methods, that ensure optimum rapidity and optimization of mechanical actions to the mechanical part of device and optimization of power consumption. Ill.10, bibl. 12 (in English; summaries in Lithuanian, English, Russian).

Г. Блажюнас, В.А. Гяляжявичюс. Исследование точности многофункциональной двухкоординатной системы // Электроника и электротехника. – Каунас: Технология, 2004. – № 2(51). – С. 8-14.

Статья предназначена для исследования характеристик двухкоординатной системы; здесь обсуждается абсолютная и повторяющаяся точность. Оценивается, как разные методы управления влияют на точность двухкоординатной системы, которая может работать в режимах позиционирования и сканирования. Большое внимание уделяется методам управления, которые обеспечивают оптимальную скорость, увеличивают долговечность и снижают энергетические расходы прибора. Результаты экспериментов с производственными приводами показывают, что повторяющаяся точность многофункциональной двухкоординатной системы не ухудшается, используя методы управления, которые обеспечивают оптимальную скорость, увеличивают долговечность и снижают энергетические расходы. Ил. 10. библ. 12. (на английском языке; рефераты на литовском, английском и русском яз.).