The Study of the Problems of the Master-Slave Teleoperation Control Anthropomorphic Manipulator

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***Abstract*—This article describes the problems of anthropomorphic manipulators (AM) master-slave teleoperation control. The aim of the work is to study the problems of the teleoperation control accuracy. The scheme of copying control system is considered in the article. The most characteristic problems for this control method are allocated. The discretization and restoring of the signal examples describing the rotation angle dependence of the manipulator joint on time are made. Real-time smoothing methods based on the calculation of the speed and acceleration of the signal change, as well as smoothing by piecewise linear interpolation with a delay of one discrete time tick are applied to the restored signal. For the restored signals with smoothing and without smoothing, the root mean square of deviation from the initial signal is estimated.**

Keywords—master-slave teleoperation control, anthropomorphic manipulator, exoskeleton, encoder, signal discretization, signal interpolation

I. Introduction

At present, the task of ensuring accurate reproduction of the operator's actions in remote copying control of robotic means is relevant, since there is a need to replace a person when performing work in difficult conditions that pose a danger to life and health. Much attention is paid to manipulators with anthropomorphic kinematic structure, as they allow the most accurate reproduction of the operator's hand movements.

The purpose of this work is to study the accuracy problems of the master-slave teleoperation of an anthropomorphic robot.

In this study, the influence of the control signal discretization on the anthropomorphic manipulator teleoperation accuracy is considered. The object of the study is a teleoperation system, in which following methods are used:

- a method for the direct kinematics problem solving using the Denavit-Hartenberg representation [1] to register the positions of the anthropomorphic manipulator joints;
- a method for the dynamics problem solving by predicting the movements of the operator's hand to form the laws of motion of the anthropomorphic manipulator nodes [2].

According to the results of the study published in [3], one of the typical problems of remote control systems is the presence of a delay. It leads to increase of time required to perform tasks, an increase in the number of errors, as well as a decrease in the level of confidence in the system as a whole.

Thus, one of the main requirements for the teleoperation control system is the reproduction of the manipulator joints rotation angles of the master device with sufficient accuracy and minimum time delay.

This requirement is most critical for medical applications such as microsurgery [4]. In the work [5] the influence of surgical robotic systems master devices parameters on the accuracy and efficiency of task performing was studied. Control accuracy is also important for space robots [6] and rescue robots.

In the case of using the digital systems, there are inevitable losses of accuracy due to the digital-analog conversion of control signals (signal time discretization and level quantization).

Modern sensors of rotation angles (encoders) have a bit depth of 12 and more. The use of such encoders allows to determine the rotation angle with an accuracy of at least 0.05 degrees at acceptable values of the rotation angle in the range from 0 to 180 degrees. Such accuracy values are sufficient to solve the problems of anthropomorphic manipulator master-slave teleoperation, so this kind of deviation can be neglected in this study.

The reconstruction of the analog signal from the discrete sequence of values can be performed with high accuracy using the Kotelnikov theorem. However, the application of this theorem in the field of teleoperation is limited by the fact that to restore the value of the signal level at the current time, it is necessary to have information not only about the previous discrete time ticks, but also about the subsequent ticks. This limitation contradicts the requirement of providing a minimum delay and the principles of real-time systems functioning as a whole [7].

II. Methods

A. The task statement

The kinematic scheme of the anthropomorphic manipulator considered in this article is presented on Fig. 1. The manipulator has 7 degrees of rotational mobility A_1-A_7. Symbols B_1, B_2 B_3 correspond to the shoulder, elbow and wrist nodes, B_4 is the end effector. Similar kinematic scheme is used in anthropomorphic robots AR-600 [8], SAR-400 [9]. There are other models of manipulators based on this scheme [10], [11].

The master device by means of which the teleoperation of the anthropomorphic manipulator is carried out is an upper-limb exoskeleton. Upper-limb exoskeleton has a kinematic scheme similar to the kinematic scheme of the manipulator. An example of such devices is the master device of the copying manipulator [12].

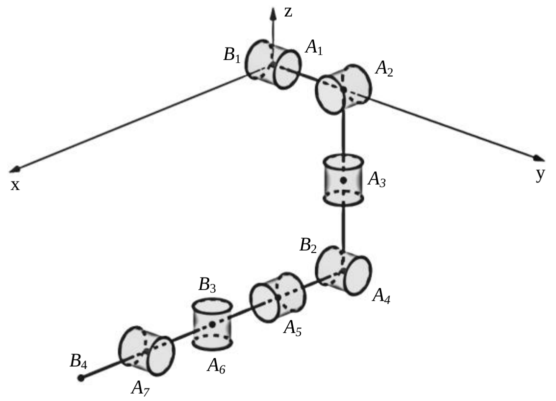

Fig. 1. Kinematic scheme of anthropomorphic robot manipulator with 7 degrees of mobility.

Teleoperation system of the anthropomorphic manipulator (Fig. 2), besides master device and the manipulator also includes PC, anthropomorphic manipulator control module, video surveillance device (video camera), display (monitor) and a communication channel. The communication channel is used for transmitting commands to the control module and the video sequence generated by the video camera to the operator's PC.

The PC performs the following functions:

- acquisition and processing of data on the rotation angles of the master device joints;
- formation and transmission of commands to the manipulator control module;
- receiving and decoding the video stream coming from the video camera.

Each command for the control module of the anthropomorphic manipulator is a vector θ of the rotation angles of the joints corresponding to the seven degrees of manipulator mobility:

$$\theta = \{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6, \theta_7\}. \quad (1)$$

If the encoders used in the master device and corresponding encoders of the manipulator are identical, the angles θ_i, $i = \overline{1..7}$, can be represented directly in the code used by the encoders to reduce the delays and computational costs associated with converting the data into an intermediate format.

On the basis of the received commands, the control module generates signals for the electric motors, tracking the rotation angle of each joint with encoders coupled with the electric motors.

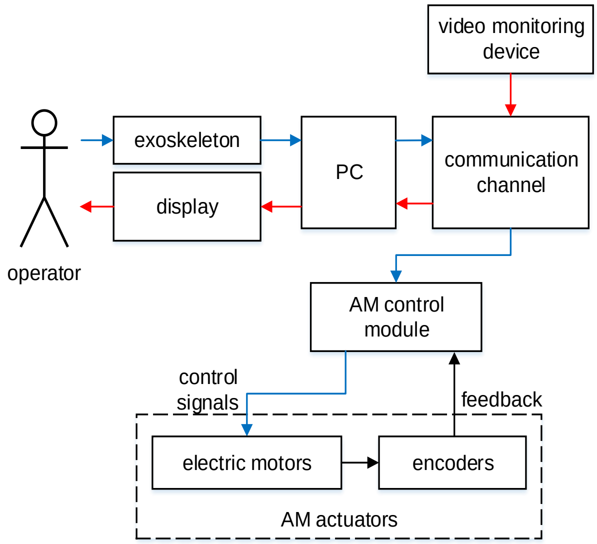

Fig. 2. Diagram of the teleoperation system of anthropomorphic manipulator.

The total delay in the AM teleoperation system is the sum of delays that occur in the following stages of the system:

- receiving and processing data on the position of the operator's hand;
- commands formation for the AM control module;
- formation of data packets according to used information transmission protocol;
- commands transmission over the communication channel;
- receiving and processing commands by AM control module, the formation of control signals for electric motors of actuators;
- changing the spatial position of components of the AM mechanical system according to the received commands;
- image capture and video encoding by video camera;
- transmitting the video stream over a communication channel;
- video stream receiving and decoding;

- image output to the display device (monitor).

The most specific delays for anthropomorphic robot teleoperation system are:

- receiving and processing data on the position of the operator's hand;
- commands formation for the AM control module.

The absence of mechanisms meant to reduce the level of sampling error in the AM teleoperation system can lead to undesirable consequences. One of them is the vibration caused by a sharp transition of the spatial configuration of the manipulator from the state corresponding to (k-1)-th discrete time tick to the current state corresponding to the k-th tick. Increasing the sampling rate minimizes this effect, but also increases the bandwidth requirements. Thus, the actual scientific task is to study ways to reduce the level of signals sampling error in the teleoperation system. To investigate the problem, the following steps will be performed:

- discretization of the signal that describes the dependence of the rotation angle of the manipulator joint on time when performing tasks;
- restoration of the signal in several possible ways;
- estimation of the resulting error value for different recovery methods.

B. Method of study

The study proposes to assess the dependence of the signal that describes the rotation angle of the master device joints in time discretization error level on the sample rate for the following cases:

- restoration of a signal without smoothing;
- restoration of the signal with smoothing that does not require an increase of delay (close to real-time mode);
- signal recovery with smoothing based on the delayed execution of the incoming commands.

Signals for the study were obtained by simulating the process of moving the manipulator while avoiding obstacles in the working area (Fig. 3). The time from the beginning to the end of the process was T=1 s.

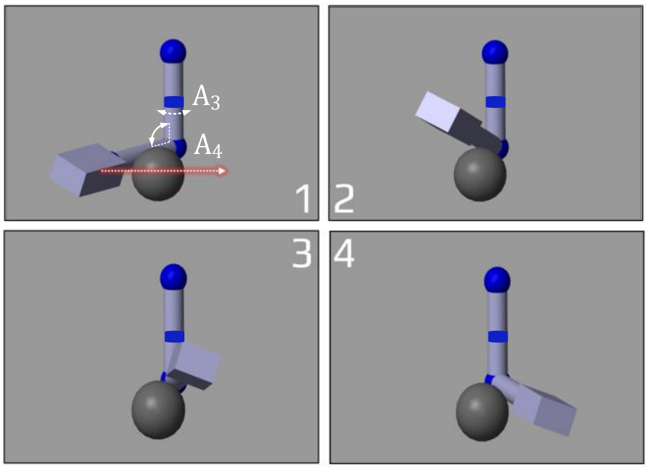

Fig. 3. Moving the manipulator while avoiding an obstacle.

When the manipulator is moved, the rotation angles of the joints A_3 and A_4 are being changed. The dependence of the rotation angle of the joint A_3 on time is approximated by the function

$$s(t) = \begin{cases} 45, \ t < 0, \\ 45 + 90t, \ 0 \le t < 1, \\ 135, \ t \ge 1. \end{cases} \quad (2)$$

The dependence of the rotation angle of the joint A4 on time is approximated by the function

$$q(t) = \begin{cases} 90, \ t < 0, \\ 90 - 45\sin(\pi t), \ 0 \le t < 1, \\ 90, \ t \ge 1. \end{cases} \quad (3)$$

Graphs of these functions are shown in Fig. 4.

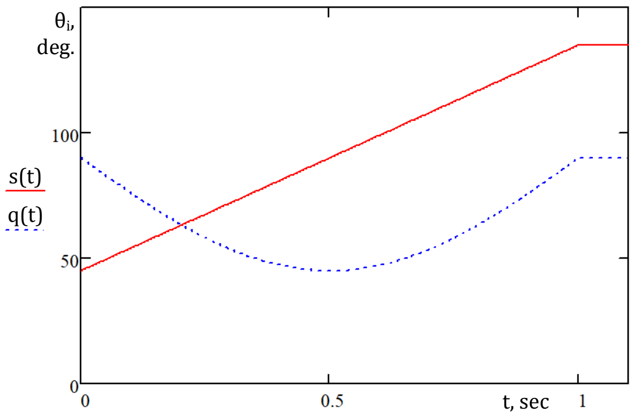

Fig. 4. Graphs of time dependence of rotation angles of joints A3 and A4.

To obtain a function corresponding to an arbitrary signal z(t), restored after sampling in time with a frequency f Hz, the following formula can be used:

$$z_1(t,f) = z\left(\frac{\lfloor tf \rfloor}{f}\right). \quad (4)$$

Graphs of the restored functions $s(t)$ and $q(t)$ at f = 20 Hz are shown in Fig. 5.

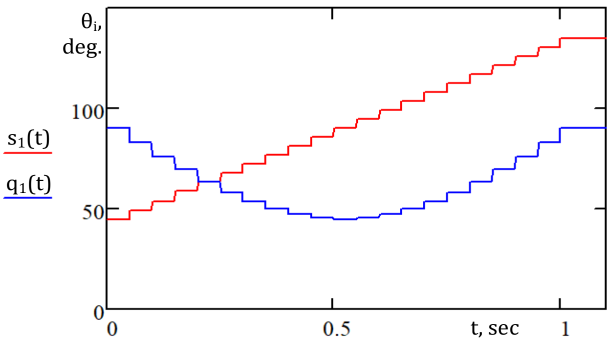

Fig. 5. Signals $s_1(t)$and $q_1(t)$ after discretization and restoration of signals $s(t)$ and $q(t)$.

The criteria for the selection of signal smoothing methods are the low computational complexity of the algorithm and the minimum increase in the response time of the manipulator. The following ways of smoothing were selected:

- calculation of the angle value on the next discrete time tick based on the assumption of a constant value of the angle change rate;
- calculation of the angle value on the next tick based on the assumption of the angle change with constant acceleration;
- piecewise linear interpolation of the time dependence of the joint rotation angle.

The first method of smoothing is based on the calculation of the average speed $v(t)$ of the change of the rotation angle of the joint θ_i between the previous tick $(t-\frac{1}{f})$ and the current tick t:

$$v(t) = \left(\theta_i(t) - \theta_i\left(t-\frac{1}{f}\right)\right)f. \tag{5}$$

The angle continues to change at speed v until a new value of θ_i arrives at the time $\left(t+\frac{1}{f}\right)$ after which the process is repeated.

An example of smoothing signals $s_1(t)$ and $q_1(t)$ in this way is shown in Fig. 6.

The second method of smoothing is based on the calculation according to (5) the average rate of change in the angle between the two previous ticks (v_2), as well as between the previous and the current tick (v_2) :

$$v_1 = v(t-\frac{1}{f}), \tag{6}$$

$$v_2 = v(t). \tag{7}$$

The values v_1 and v_2 are used to calculate the estimated average speed v_3 of the rotation angle of the joint θ_i between the current and next ticks, taking into account the average acceleration a:

$$a = (v_2 - v_1)f, \tag{8}$$

$$v_3 = v_2 + \frac{a}{2f} = v_2 + \frac{v_2 - v_1}{2}. \tag{9}$$

An example of signals $s_1(t)$ and $q_1(t)$ smoothing by this method is shown in Fig. 7.

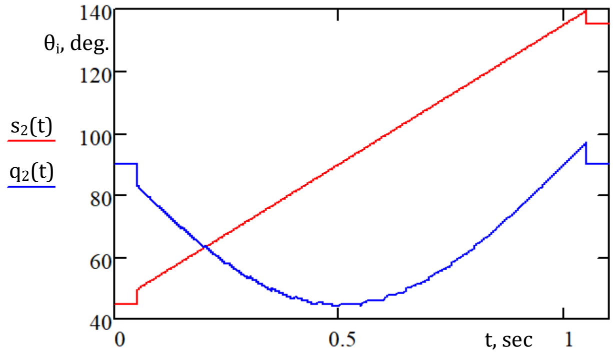

Fig. 6. Signals $s_2(t)$ and $q_2(t)$ obtained from signals $s_1(t)$ and $q_1(t)$ as a result of smoothing based on the calculation of the average speed.

In contrast to the considered methods, the smoothing of the signals by the method of piecewise linear interpolation introduces an additional time delay, the value of which is $\frac{1}{f}$. The angle transfer command θ_i in the state $\theta_i(t)$ is carried out after the arrival of the following commands at time $\left(t+\frac{1}{f}\right)$. In this case, the change in the rotation angle occurs at a speed $v\left(t+\frac{1}{f}\right)$, calculated in accordance with (5).

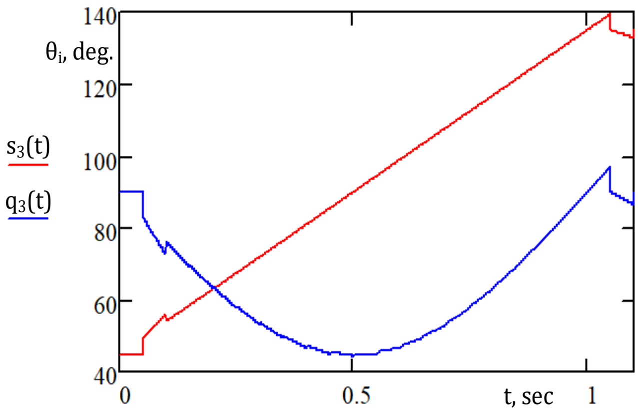

Fig. 7. Signals $s_3(t)$ and $q_3(t)$ obtained from signals $s_1(t)$ and $q_1(t)$ as a result of smoothing based on the acceleration calculation.

An example of smoothing signals $s_1(t)$ and $q_1(t)$ by piecewise linear interpolation is shown in Fig. 8.

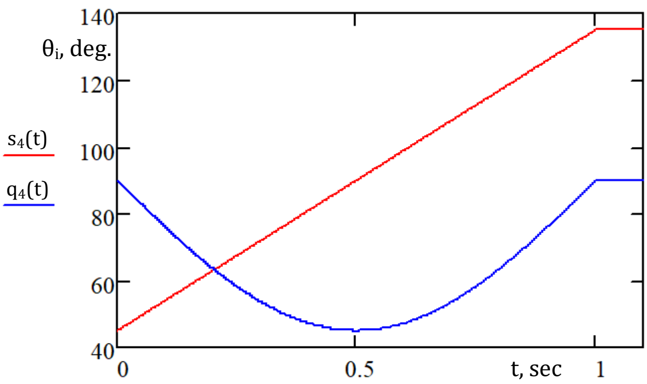

Fig. 8. Signals $s_4(t)$ and $q_4(t)$ obtained from signals $s_1(t)$ and $q_1(t)$ as a result of smoothing by piecewise linear interpolation.

The error resulting from the discretization and restoration of the signal is estimated by finding the standard deviation σ_z of the resulting signal $z_1(t)$ from the original signal $z(t)$:

$$\sigma_z = \sqrt{\frac{1}{T}\int_0^T \left(z(t) - z_1(t)\right)^2 dt}. \quad (10)$$

III. Results

For Fig. 9, 10 graphs of the dependence of the RMS error on the sampling rate for the signals considered in section 2 are given.

The method of smoothing the restored signal by piecewise linear interpolation based on the average rate of change of the signal between the current and the next tick has the best indicators (the minimum RMS deviation from the original signal). However, the disadvantage of this approach is the increase in the control delay of the anthropomorphic manipulator for a time equal to one step of the discretization.

Signal smoothing methods based on the use of average speed and acceleration values between the previous counts allow to avoid additional delay, but significantly distort the trajectory of the manipulator at low sample rates. With increasing of the sample rate, the efficiency of these methods increases significantly.

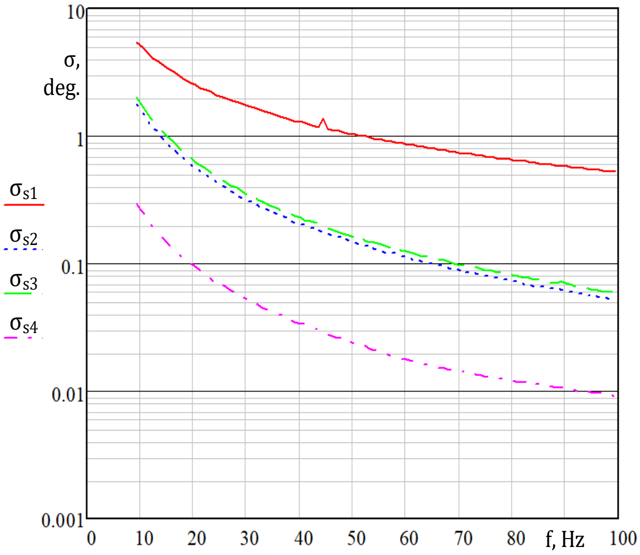

Fig. 9. Dependence of the RMS error value from the sampling rate for the considered methods of signal recovery $s(t)$.

When using the speed-based signal smoothing method, the standard deviation value is slightly lower than for the acceleration-based smoothing method. On Fig. 11 graphs of the restored smoothed signal deviation at $f = 20$ Hz are presented:

$$d_{q2}(t) = q(t) - q_2(t), \quad (11)$$

$$d_{q3}(t) = q(t) - q_3(t). \quad (12)$$

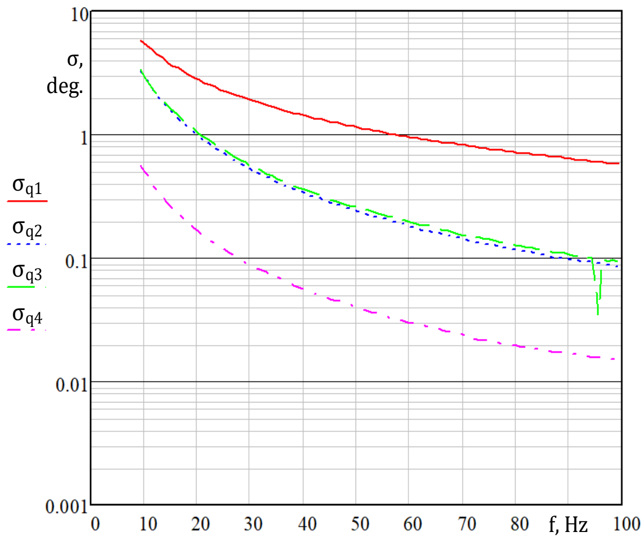

Fig. 10. Dependence of the RMS error value on the sampling rate for the considered methods of signal recovery $q(t)$.

At the beginning and end of the manipulator movement on the charts there are emissions due to the rapid change in the values of speed and acceleration at the break points $t = 0$ and $t = 1$ of the approximating function (3). At the same time, the signal $q_2(t)$ obtained as a result of smoothing the signal $q_1(t)$ based on acceleration, has longer emissions than the greater value of the standard error value. However, with relatively small changes in speed and acceleration between adjacent counts, the acceleration-based signal smoothing method is more efficient than the speed-based method.

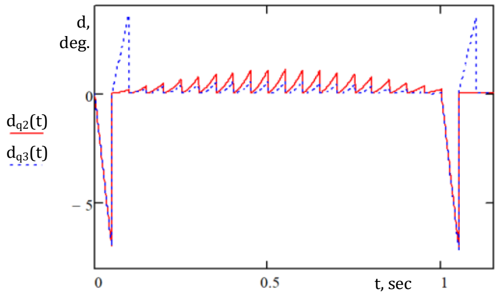

Fig. 11. Deviations arising from smoothing the signal $q_1(t)$ by methods based on the calculation of speed and acceleration at $f = 20$ Hz.

In addition, the amplitude and absolute duration of emissions are reduced by increasing the sample rate (Fig. 12).

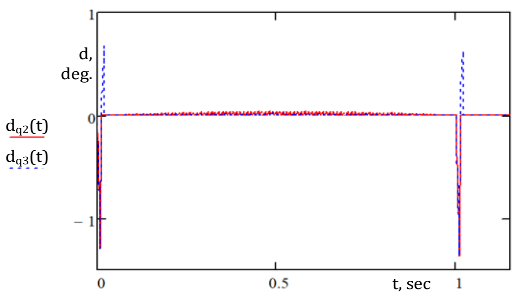

Fig. 12. Deviations arising from $q_1(t)$ signal smoothing by methods based on speed and acceleration at $f = 100$ Hz.

Short emissions can be suppressed by software or hardware filters, or smoothed by the inertia of the manipulator mechanical system.

IV. Discussion

In this paper the problems of the influence of the signal discretization on the accuracy of the anthropomorphic manipulator teleoperation are considered. The signal that is restored from the discrete sequence of the angles values by the anthropomorphic manipulator control module has a stepped character. That can cause spurious vibration of the manipulator when signal on a drives is raw.

The main attention is paid to the methods of signal smoothing based on extrapolation of the signal values on the time interval between the current and the next discrete time tick, taking into account the known speed and acceleration of the signal change between the previous and current ticks. Despite the fact that the method of smoothing the signal by piecewise linear interpolation allows to achieve less misalignment between the signal before sampling and the resulting signal, its usage leads to delay increase.

A promising area of research is the development of methods for predicting the value of the signal at the next discrete time tick with the use of neural networks, pre-trained on real samples of signals arising in the copying control system in the process of performing target tasks with the anthropomorphic manipulator. The achieved prediction accuracy is higher, the more data will be used to train the neural network [13]. Since forecasting must be done in real time, the performance of such solutions, as well as the requirements for computing resources of the system, require further study. In the future, it is planned to conduct research related to the subject of this work on real robots.

V. Conclusion

The problems of teleoperation control of anthropomorphic manipulators caused by the discretization of the signal describing the process of changing the rotation angles of the master device joints are considered in this paper. The scheme of the copying control system is considered, the most typical problems of this type of control are described. The discretization and restoration of the signal examples are performed. Real-time smoothing methods based on the speed and acceleration of the signal change, as well as smoothing by piecewise linear interpolation with a delay of one discrete time tick are applied to the restored signal. For the restored signals with smoothing and without smoothing, the standard deviation from the initial signal is estimated.

As a result of the study, it can be concluded that a method of smoothing the signal by piecewise linear interpolation shows the best indicators (the minimum deviation value). If it is necessary to ensure a minimum control delay, it is advisable to use smoothing methods based on the assumption of changing the angle at a constant speed or constant acceleration. At the same time, the method of smoothing based on the calculation of the average speed provides slightly lower emissions of the error level with a sharp change in speed, and the method based on acceleration allows to provide a lower average error level with a smooth change in speed.

Acnowlegments

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