Energy efficiency assessment of anthropomorphic manipulator control algorithm

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Abstract. Currently, developers of robotic systems are very interested in intensively developing unmanned technologies, the concept of which is to use robots to perform routine, harmful and dangerous types of work without direct human participation, which is the key to ensuring safety and high efficiency of solving tasks. Active research is conducted in the field of artificial intelligence and the development of anthropomorphic robots (AR). Modern ARS are not yet able to completely replace a person when performing complex tasks in a dynamic environment. The inability of such robots to completely replace a human is due to the short duration of work in offline mode. The reasons for the short duration of the AP are the low capacity of modern batteries and high power consumption of software and hardware components of the robot. The solution to this problem is possible by developing and modifying mathematical methods and algorithms for performing target operations in order to minimize energy consumption. The article assesses the energy efficiency of the algorithm for copying control of an anthropomorphic manipulator.

1. Introduction

Modern Autonomous anthropomorphic robots face a number of problems, one of which is the low duration of their work. This type of robot is designed to operate in conditions that are dangerous to human life – in space, under water or under high radiation, to perform irregular operations – rescue operations, maintenance of space equipment, equipment for nuclear facilities, research missions, etc. Execution of the main target operations of these robots is performed by Executive devices – anthropomorphic manipulators (AM).

The power consumption of manipulators depends on the way of its movement, so the application methods energy-efficient path planning will increase the duration of the work and time of useful work (less need to spend time recharging or changing the energy element) and the battery life (a limited number of cycles charge/discharge).

In modern robotics, the problem of limited energy resources of autonomous anthropomorphic robots (AR) is relevant. Numerous scientific researches are devoted to the solution of the presented problem, among the most known tendencies it is possible to allocate the following: studying of new strong and easy materials, creation of perspective powerful power sources, variations of odification and optimization of AR structure, the solution methods development of energy-efficient movement management problems.
The authors are particularly interested in the problem of planning an energy-efficient motion path (MP) for redundant AR manipulators. In this area, a number of papers dedicated to the development of methods and algorithms for planning the energy-efficient path of the AR manipulator in the work area with an obstacle [1-4].

The tasks of motion path planning of manipulators with redundant mobility in the working area with obstacles have been developed since the 1980s [5]. Motion generation for redundant manipulators is usually considered with using kinematic control [6]. The task of finding redundant manipulators motion path is often to find any valid way from an infinite number of options. The solution of this problem is to construct a polyline curve of the displacement line for its subsequent approximation by cubic splines and the transition to the solution of dynamics problems. The tasks of optimal motion path constructing according to the given selection criteria are more relevant in applied research. The basis of problems of optimum values search is put in [7-8]. When solving the optimal path-finding problem according to the established quality criteria, a problem of high computational complexity arises [9-10].

There are many efficient but computationally complex methods for planning the path of a manipulator. Two approaches to trajectory planning are widely covered in the literature - the approach based on graph theory, as well as spline interpolation. The first approach is associated with great computational complexity, and the second – with the complexity of selecting reference points, excessive movement for a small number of them, and the complexity of calculations for a large one.

Planning the trajectory of movement of redundant manipulators based on evolutionary approaches is considered in [11-13]. The proposed solutions are aimed at obtaining an accurate solution both in offline mode and in real time, but do not take into account the power consumption of the manipulator motors when moving.

Methods for constructing the trajectory of the manipulator movement based on learning the natural movements of the human hand are presented in [14-15]. At the same time, there are problems with the computational complexity of the proposed solutions, and the natural optimization of human hand movement does not meet the requirements for performing the operation with minimal energy consumption.

Numerical methods for solving the trajectory planning problem are presented in [16-17]. The execution of trajectory generation procedures in these works has a high computational complexity, which requires high performance of the computing system.

Based on this, it is an urgent task and purpose to develop energy-efficient path planning methods for manipulators operating in real time or close to it.

2. Analyze of problems of energy consumption of manipulators of autonomous anthropomorphic robots when performing target operations

The current pace of development of anthropomorphic robotic systems is due to the tendency to replace a person when performing potentially dangerous work. Thus, researchers face a number of tasks that will allow them to replace a person in various fields of activity, including rescue operations, space missions, work in radiation conditions, during fires, military operations, and natural disasters. One of these tasks is to increase the duration of target operations performed by the robot in offline mode.

The structure of the AR's power consumption depends on the number of operations performed in its modules [18]. The modular structure of the AR implies the presence of transport (pedipulators), Executive (manipulators), service (sensors, sensors, displays, etc.) and control (processors, controllers, etc.) modules.

Existing methods of reducing the power consumption of AR manipulators can be divided into two types: design modification and modification of motion control algorithms. Let's consider the advantages and disadvantages of the presented methods. The advantage of reducing energy consumption by modifying the design of the AP manipulators and modifying the motion control algorithms is shown in table 1.
Modification of the AR design should be carried out at the design stage, since the replacement of components, parts and engines in existing samples is associated with great, sometimes insurmountable difficulties and requires recalculation of the system dynamics of the manipulator, compatibility, etc. Modification of motion control algorithms includes modification of methods for planning the path of movement and modification of methods for planning the trajectory of the manipulators of the anthropomorphic robot [19]. By the method of path planning of the manipulator refers to the planning of the route of the manipulator from the starting point \( A \) to the end point \( B \), including intermediate points [20]. In other words, searches basic start and end coordinates of the united successive lines of the route and the values of generalized coordinates of the manipulator in the configuration space.

**Table 1.** Advantages and disadvantages of methods for reducing power consumption of the manipulator.

| Method description                                      | Advantages                                                                                   | Disadvantages                                      |
|---------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------|
| Facilitating the construction of the manipulator, i.e. using strong and light materials | Reducing the weight of the manipulator; reducing the requirements for the power of electric motors | Significant increase in the cost of construction   |
| Choice of economical electric motors with high efficiency | Reduced engine power consumption                                                              | Increased engine wear and construction costs       |
| Reducing the number of degrees of mobility of the manipulator | Simplified design, reduced cost                                                               | Reduced mobility of the manipulator, possible increase in the number of manipulator operations |
| Modification of methods for planning the path of movement of the manipulator | Reduced energy consumption due to optimal travel path                                         | There may be a slight increase in the path of movement of the manipulator                     |
| Modification of methods for planning the trajectory of manipulators | Reducing energy consumption by building an optimal path for the movement of links              | It is possible to reduce the speed and accuracy of performing target operations with the manipulator |

Planning the path of movement of the manipulator includes continuous intervals between points, the movement between which is carried out using methods of planning the trajectory of movement. To solve these problems, it is possible to use a combination of solving the forward and reverse dynamics problem in conjunction with forecasting methods [21].

The use of these methods is also relevant for reducing the power consumption of manipulators [22]. Among the disadvantages of these methods, we can highlight a decrease in indicators for evaluating motion control algorithms, which include accuracy, path length and speed, and computational complexity.

The main operations to reduce the energy consumption of manipulators in motion control algorithms are solved at the stage of planning the trajectory of the manipulator, which is not correct, since the problem of energy efficiency is also relevant for methods of planning the path of movement. The search for the shortest path is not optimal due to the possibility of performing more movement by the link located at the base of the manipulator, the engine of which is more powerful and consumes more energy.
3. Problems of copying control of an anthropomorphic manipulator

One of the main requirements for the copying control system is that the manipulator reproduces the rotation angles of the joints of the master device with sufficient accuracy and minimal time delay.

When using digital systems, there is inevitably a loss of accuracy due to digital-to-analog conversion of control signals (signal sampling by time and quantization by level).

Currently existing angle sensors for copying devices (encoders) have a bit rate of 12 or more bits. The use of encoders of this size allows you to determine the angle of rotation with an accuracy of at least 0.05 degrees with acceptable values of the angle of rotation in the range from 0 to 180 degrees. Such accuracy indicators are sufficient to solve the problems of copying control of an anthropomorphic manipulator, so the error of encoders in this study can be ignored.

Recovery of an analog signal from a sequence of discrete samples can be performed with high accuracy using Kotelnikov's theorem. However, the theorem can be applied in the field of copy control is limited by the fact that the recovery of the value of the signal level in the current time you must have information not only about the preceding and the subsequent counts, which contradicts the requirement for low latency and principles of real-time systems in General.

Figure 1 shows the kinematic scheme of the anthropomorphic manipulator considered in this article. The manipulator has 7 degrees of rotational mobility of the A1 – A7. The designations B1, B2 B3 correspond to the shoulder, elbow and wrist nodes, B4-the working end.

![Kinematic diagram of an anthropomorphic robot manipulator with 7 degrees of mobility](image)

The master device, which is used to copy the control of an anthropomorphic manipulator, is an exoskeleton of the upper extremities, which has a kinematic scheme similar to the kinematic scheme of the manipulator. An example of such devices is the master device of a copying manipulator [23].

The system may control an anthropomorphic manipulator, except setting device and of the manipulator also includes a computer control module anthropomorphic manipulator device video surveillance (video), the display device of the video (monitor) and a communication channel through which the command transmission control module and of the video generated by the video monitoring device, on a computer operator.

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

\[
\theta = \{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6, \theta_7\}
\]
If the master and manipulator use the same rotation angle sensors (encoders), the angles $\theta_i, i = 1..7$ can be represented directly in the code used by the encoders to reduce the latency and computational costs associated with converting data to an intermediate format.

Based on the received commands, the control module generates signals for the electric motors, tracking the angle of rotation of each joint by means of encoders connected to the electric motors.

The total delay in the am copying control system is caused by delays that occur at the following stages of the system operation:

- receiving and processing data about the operator's hand position;
- forming commands for the AM control module;
- formation of data packets corresponding to the information exchange Protocol used;
- sending commands over the communication channel;
- receiving and processing commands by the AM control module, generating control signals for electric motors of Executive devices;
- changing the spatial position of the components of the mechanical AM system according to the received commands;
- image capture and encoding of the video stream by the video monitoring device;
- transmitting a video stream over a communication channel;
- receiving and decoding the video stream;
- output the image to the display device (monitor).

The most specific of these delays for copying control of an anthropomorphic manipulator are:

- receiving and processing data about the operator's hand position;
- forming commands for the AM control module.

The absence of mechanisms for reducing the level of sampling error in the copying control system can lead to undesirable vibrations associated with a sharp transition of the spatial configuration of the manipulator from the state corresponding to the (k-1)-th sample of discrete time to the current state corresponding to the k-th sample. Increasing the sample rate minimizes this effect, but also increases the bandwidth requirements of the communication channel.

4. Conclusion

The use of analytical methods of path planning is relevant in problems of path planning at a large sampling step, but this negatively affects its computational complexity. Thus, it is important to develop this direction in the direction of reducing the complexity of the algorithm, for example, when presenting an obstacle with a geometric primitive and developing energy efficiency criteria when searching for a route.

To search for a path, the criteria for finding the shortest route or any acceptable solution is used, but the problem of energy consumption is not solved. Therefore, since the shortest path is not always optimal in terms of energy consumption, the task of developing an energy-efficient method for planning the travel path for an anthropomorphic robot manipulator in a work zone with a stationary obstacle in real time is relevant.

Abstract similarity of the operator's hand positions and the AR can be implemented in various ways. Similarity can be achieved due to the same rotation angles in the operator's hand joints and AR joints.

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