High-speed algorithms for automatic manipulators control systems

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Abstract. This article presents options for implementing high-speed algorithms for controlling automatic manipulators operating as part of robotic complexes (RTCs). Software control systems for automatic manipulators with the use of noise-resistant coding algorithms are considered in the conditions of operation in production conditions, when there is instability in the supply of energy resources, the presence of sources of network interference, interference that violates the safe working conditions of radio-electronic equipment. Examples of implemented control algorithms with different software cycles are given, regarding into account the peculiarities of production. A comparative analysis is made with analogs that have similar technological characteristics.

1. Introduction
In technological processes where automatic manipulators (figure 1) are used, there is a problem of limiting the acceleration of the working body, the grip. If the accelerations of the allowed values are exceeded, shock loads, displacement of parts in the grip, and deformation phenomena occur. This leads to disruption of technological processes and emergencies [1]. Special high-speed control algorithms are required to create optimal dynamic processes of AM movements and achieve maximum performance.

Algorithms based on interactive prediction of motion parameters with the use of basic functions are the options that allow increasing the performance [2].

Figure 1. Block diagram of the control system with a high-speed algorithm: SEB – sensors of manipulator's Executive bodies; AM – automatic manipulators, EB – the Executive bodies.
2. The predictability of the system

An option for creating a forecast system is shown in figure 2. This variant differs from the standard methods of foreign robotics by the presence of an interactive system. In this scheme, the time for decision-making is significantly reduced, which makes it possible to improve the speed and quality of regulation in comparison with typical proportional control schemes.

The predicted reference trajectory 1 provides a smooth transition of the controlled process 3 to the specified trajectory 2 with the elimination of undesirable overloads from exorbitant accelerations.

A significant factor is that the reference trajectory forms the behavior of the dominant part of the regulatory system.

![Figure 2. Option for creating a forecast system.](image)

In this case, the inertial properties of the system, the main dynamic characteristics, in particular, the time constants of the main elements in the control loop, are taken into account.

The strategy of the computer system is based on ensuring a minimum deviation of the predicted controlled value from the reference trajectory under temporal restrictions on the control and state coordinates. Solving this problem requires the use of a high-speed algorithm to work in real time.

3. Methods for improving the performance of manipulator control algorithms

To obtain a high-speed algorithm, we should limit the variety of control actions by using a set of functions:

\[ u^*(i + k) = \sum_{j=0}^{N} a_{j}u_{j}(k), \quad (k = 0,1,\ldots,N), \]

where \( u_{j}(k) \) is the activating functions in the form of a unit jump, exponent, etc.; and \( j \) is the corresponding weight function.

At the same time, cases of resonant phenomena are detected and predicted to be eliminated [3, 4]. When using external information about coordinates and movement dynamics, the greatest accuracy is achieved, since its database contains data about hidden effects, the influence of system stiffness and backlash, which significantly affect the trajectory of movement in extreme conditions.

The maximum \( A_C \) indicator can be used as a criterion for the speed efficiency of the computing device algorithm, in particular, the speed of the manipulator control system:

\[ A_C = I / T_c, \quad (1) \]

where \( I \) – the amount of information given out per clock cycle; \( T_c \) – the total duration of the task in binary units.

When summing \( Q \) numbers of digits \( N \), the total duration of the task in binary units:

\[ T_c = Q \cdot N. \]

Amount of information including non-recurring amounts: \( I = \log_2(Q(2^N - 1)) + 1 \).

If the number of digits \( N \) is more than eight, the influence of the values "-1" and "+1" in this expression is practically excluded.
Thus, the criterion for the speed efficiency of the computing device algorithm will be as follows:

$$A_c = \log_2(Q \cdot 2^N) / (Q \cdot N) .$$

(2)

The graph of the computing device efficiency depending on the number of operations and the number of digits is shown in figure 3.

![Graph of the efficiency of the computing device](image)

**Figure 3.** Graph of the efficiency of the computing device $A_c = I / T_c$, depending on the number of operations $Q$ and the number of digits $N$.

For example, if the duration of adding two numbers $t_c = 1 \text{ ms}$, the duration of write/read operations is negligible, then the time of adding ten to eight digits in a normal adder to get all the sums $Q$ for a period of time $t_c$ calculation speed $V_{c1} = 8 \cdot 10^6 \text{ bits/s}$.

If we create an algorithm so that the sums found once in the future are not calculated, but read from memory (high-speed computing device-HSC), then the average speed of calculations will be:

$$V_{c2} = \log_2(Q \cdot 2^N) / (Q \cdot t_c) = 1.13 \cdot 10^6 \text{ bits/s} .$$

Thus, the algorithmic efficiency in comparison with a typical (unified computing device – UCD):

$$S = V_{c1} / V_{c2} = 8 \cdot 10^6 / (1.13 \cdot 10^6) = 7 .$$

That is seven times higher.

A radical solution to the problem of increasing high-speed algorithmic efficiency is to use high-speed computing devices, in particular, in the form of automata with rigid logic, provided with memory and algorithms that do not require labor-intensive computing operations [11].

Variants of such devices are devices for controlling an automatic manipulator of the SPU-3 type, intended for operation as part of robotic complexes [1].

Parallel circuits and multiprocessor systems are used to speed up computing processes [3, 7].

However, when they work, there are problems that reduce the speed characteristics of the system as a whole. In complex N-processor systems, the features of simultaneous operation of processors are the presence of numerous sequential operations in the algorithm, the occurrence of conflicts on a common basis, and so on. At the same time, the performance of multiprocessor systems is limited. In particular, the performance of the $P_p$ under the condition of the same speed of all calculators is determined in accordance with Amdahl's law [3]:

$$P_p = N / \lg N .$$

The performance growth limit depends on the execution time of the slowest operation in some parallel link. Program acceleration using multiple processors is limited by the size of the sequential
part of the program. Even if we parallelize 95% of the program, theoretically the maximum acceleration will be 20 times, regardless of how many processors are used.

If \( p \) is the number of parallel nodes, \( \alpha \) is the share of sequential operations, and \((1-\alpha)\) is the share of parallel operations, the value of the accelerated process \( S \) in comparison with the single-processor version is determined by:

\[
S = \frac{1}{(\alpha + (1-\alpha)/p)}.
\]

The calculation table shows that only an algorithm that excludes sequential calculations (\( \alpha=0 \)) makes it possible to obtain a linear increase in performance with an increase in the number of computers in the system [3, 7]. If half of the operations are sequential, the total increase will never exceed two times.

**Table 1. Efficiency of algorithms, if there is a percentage \( \alpha \) of sequential calculations.**

| \( \alpha \) | 1  | 2  | 4  | 8  | 10 |
|-----------|----|----|----|----|----|
| 0         | 1  | 2  | 4  | 8  | 10 |
| 0.10      | 1  | 1.82 | 3.1 | 4.54 | 5.25 |
| 0.20      | 1  | 1.67 | 2.5  | 3.23 | 3.58 |
| 0.30      | 1  | 1.54 | 2.06 | 2.56 | 2.80 |
| 0.40      | 1  | 1.43 | 1.82 | 2.13 | 2.19 |
| 0.50      | 1  | 1.33 | 1.60 | 1.79 | 1.82 |
| 0.60      | 1  | 1.25 | 1.43 | 1.54 | 1.56 |
| 0.70      | 1  | 1.18 | 1.29 | 1.35 | 1.37 |
| 0.80      | 1  | 1.11 | 1.18 | 1.21 | 1.22 |

Typical operation of the manipulator in the automotive industry is shown in table 2.

**Table 2. Typical operations of the manipulator in the automotive industry.**

| Original | The Original position of the AM |
|----------|--------------------------------|
| 1        | X                              | Hand Move forward |
| 2        | Z\(^0\)                        | Decrease          |
| 3        | T                              | Capture Operation |
| 4        | Z                              | The Rise          |
| 5        | X\(^0\)                        | Hand Stroke back  |
| 6        | Y                              | Turn to the work area |
| 7        | X                              | Move hands forward |
| 8        | Z\(^0\)                        | Decrease          |
| 9        | T                              | Capture Operation |
| 10       | Z                              | Lift              |
| 11       | X\(^0\)                        | Hand Stroke back  |
| 12       | Y\(^0\)                        | Turn to the original |
|          | ORST                           | Original state    |

When creating a high-speed manipulator operating in four degrees of freedom, a variant of the synthesis of a fast code algorithm for the manipulator control system was implemented [1, 4]. The block diagram is shown in figure 4.
Figure 4. Block diagram of the control system with a high-speed algorithm: D1, D2, ..., D8-position sensors for manipulator links; T1, T2, T3, T4-information convolution triggers; T1.1, T2.2, T3.3, T4.4 -command formers; EB – the Executive bodies; SEB - sensors of manipulator's Executive bodies.

Table 2 shows typical operations of manipulators used in automotive production. These include operations: the movement of the hands (X) forward and backward, lowering and lifting (Z), the operation of grabbing the part (T) and releasing the part from the grip, turning (Y) into the work area and returning to the starting position.

| SEB | AM | EB |
|-----|----|----|
| Z   | T   | Y | X | ORST | Z | T | Y | X |
| 0   | 0   | 0 | 0 | 0   | 0 | 0 | 0 | 0 |
| X   | 0   | 0 | 0 | 1   | 0 | 0 | 1 | 0 |
| 1   | 0   | 0 | 1 | T   | 1 | 1 | 0 | 0 |
| 1   | 0   | 0 | 1 | Z   | 1 | 0 | 0 | 1 |
| 1   | 0   | 0 | 1 | T   | 1 | 1 | 0 | 0 |
| 1   | 0   | 0 | 1 | Z   | 0 | 0 | 1 | 0 |
| ... |    |   |   |     |   |   |   |   |
| 0   | 0   | 0 | 0 | 0   | 0 | 0 | 0 | 0 |

Table 3. Typical manipulator operations in automobile production.
Typical manipulator operations in automobile production is shown in table 3: Hand Move forward, Decrease, Capture Operation, The Rise, Hand Stroke back, Turn to the work area, Move hands forward.

To increase the speed of the manipulator, we can use combined parallel operations, for example:

- joint forward and downward movement: X+Z°,
- lowering with the gripper on: Z°+T,
- lifting with the capture stroke to the starting position: Z+X°,
- horizontal capture movement and rotation: X°+Y,
- before completing the turn start the movement of the capture to the goal: Y+X,

and so on...

Acceleration of the algorithm according to the scheme shown in figure 5, computing devices operate completely in parallel mode:

\[ S = \frac{1}{(\alpha + (1 - \alpha)/p) = 1/(0 + 1/4)} = 4. \]

That is, a 400% increase in productivity.

In this case, the striking effect of an 18-fold ratio of the technological acceleration of the manipulator movement to the acceleration of the algorithm in the presence of sequential operations is shown.

Synthesis of the combined manipulator algorithms shown in table 4.

**Table 4. Synthesis of the combined manipulator algorithm.**

| Sequential operations | Combined operations | Reduction time, ms |
|-----------------------|---------------------|--------------------|
|                       | Operations          | Time, ms           |                     |
| X                     | 100                 | X+Z°               | 100                 | 20                  |
| Z°                    | 20                  | Z°+T               | 20                  | 10                  |
| Z°                    | 20                  | Z°+X°              | 100                 | 50                  |
| T                     | 10                  | Z°+X°              | 100                 | 50                  |
| Z°                    | 100                 | Z°+X°              | 100                 | 50                  |
| X°                    | 50                  | X°+Y               | 500                 | 100                 |
| X°                    | 100                 | X°+Y               | 500                 | 100                 |
| X°                    | 100                 | X°+Y               | 500                 | 100                 |
| X°                    | 100                 | X°+Y               | 500                 | 100                 |
| X°                    | 100                 | X°+Y               | 500                 | 100                 |
| Y                     | 500                 | X°+Y               | 500                 | 100                 |
| Total                 | 1760                | 1440               | 360                 | α = 0.75             |

The accelerated process, S:

\[ S_{\text{pul}} = 1.23 \]

When controlling the speed modes of electric drive devices, it is necessary to take into account the inertia characteristics of the Executive bodies, in particular, the "classical time constant τ".
The duration of the transition process during acceleration and deceleration of the electric drive depends on many factors, including the value of the reduced load on the motor shaft, and the supply voltage of the electric drive.

The most dangerous shock loads on the links of the manipulator arise during the final braking. The analysis of dynamic processes at the final sections of the manipulator movement.

The figure 4 shows the calculated acceleration data depending on the length of the braking path and the initial speed \( V = 0.2 \ldots 1.0 \text{ m/s} \). On a 100 mm brake damping section with a walking speed of \( V = 1 \text{ m/s} \), the braking acceleration exceeds the typical value of the technological limit: \( \text{APR} = 15 \text{ m/s}^2 \). At a speed of \( V = 0.5 \text{ m/s} \), the damping path can be reduced to 20 mm.

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![Figure 5](image1.png)

**Figure 5.** Calculated acceleration data depending on the length of the stopping distance and speeds \( V = 0.2 \ldots 1.0 \text{ m/s} \).

![Figure 6](image2.png)

**Figure 6.** Characteristics of feed accuracy (mm) without active compensation of the Executive bodies. Charts 1, 2, 3, 4, 5... for modes 1.0, 0.9, 0.8, 0.7, 0.6 ...from the nominal value.
The range of run-out of the feed control (mm) at variable power load without active correction of movement parameters is shown in figure 6. In experimental studies of the run-out of the motor rotor, the author was able to obtain an ED control system, in which the acceleration during run-out is kept constant (figure 6). Implementation of this algorithm significantly reduces the impact of dynamic impacts.

The predicted control allows approximating the dynamic characteristics, in particular, acceleration ($A_c$, figure 7) to the optimal, calculated values.

![Figure 7](image)

**Figure 7.** Calculated ASR acceleration (mm/s$^2$) with predicted $A_c$ control and acceleration for nonsynchronous $A_a$ control.

For grabbing devices of industrial robots, acceleration is limited if the part is present. In many cases, this is 1.5·$g$ = 14.7 m/s$^2$. Figure 8 shows an experimental result of a case where the acceleration of the electric drive (1) during the run-out was maintained in an exceptionally constant mode (2).

![Figure 8](image)

**Figure 8.** Example of changing the drive speed (1) during oscillatory phenomena (2) in the power circuit.

The speed drops evenly from $\omega = 9.0$ to $\omega = 0$ s$^{-1}$. In 160 ms, the speed dropped to zero when using electromagnetic and vacuum grippers of parts in a mobile gripper.

4. Conclusion
Performance improvement is provided by algorithms with parallel processing of information while minimizing (up to elimination) the time for performing sequential computing operations.

By predicting the next technological step and combined manipulator movement operations, a significant acceleration of the process as a whole is achieved.
In particular, for 12 operations of Executive bodies, an example of obtaining a striking effect of a 15-fold ratio of the technological acceleration of the manipulator movement to the acceleration of the electronic algorithm is shown.

It is mandatory to use pre-worked interactive operations that can be instantly automatically included in the technological algorithm.

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