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Solution of the dynamics inverse problem with the copying control of an anthropomorphic manipulator based on the predictive estimate of the operator's hand movement using the updated Brown method

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Abstract. The aim of the article is the implementation of a dynamic copying control by an anthropomorphic manipulator. Dynamic control would create greater accuracy of movement and less wear on parts. A feature of the copy control is the formation of the motion law in the process of the manipulator movement, which creates difficulties for the implementation of copy control. To solve the problem, it is proposed to exchange defining the motion law of the operator's hand by its predictive estimate obtained using the updated Brown method. The results of simulation carried out on a large number of test movements show the effectiveness of the proposed solutions.

1. Introduction

One of the most important tasks of modern robotics is the development of robots to perform routine, harmful and dangerous types of work without the direct participation of humans. At the moment despite the active development of artificial intelligence technologies, robotic systems are not able to replace a person when solving complex problems in a dynamic environment. The most promising in the nearest future we consider the robots that implement the copying type of control or the so-called virtual presence of the operator. Copying control is based on the motion capture of a remotely located operator and the formation of a control signal for the robot drives. This article discusses the private task of remote presence technology, i.e. drive control of an anthropomorphic manipulator. To control the manipulator drives with a copying control type two approaches are used.

The first approach is to use tracking systems [1]. Despite the simplicity of implementation and reliability of such systems, various mechanical vibrations occur which reduce control accuracy and increase the wear of parts at high speeds of the manipulator movement and due to the lack of its movement smoothness [2].

The second approach is to control the manipulator by solving the inverse problem of dynamics. This approach is used in powerful manipulators, for which the occurrence of mechanical vibrations due to the non-smoothness of movements can lead to the failure of the manipulator [2].

The solution of the inverse problem of dynamics consists in finding the forces that must be developed in the manipulator drives in order to follow the specified law of motion. One way to resolve this problem is to solve the Lagrange-Euler equation:

$$\boldsymbol{\tau} = \boldsymbol{M}\big(\boldsymbol{q}(\boldsymbol{t})\big)\ddot{\boldsymbol{q}}(\boldsymbol{t}) + \boldsymbol{C}\big(\boldsymbol{q}(\boldsymbol{t}), \dot{\boldsymbol{q}}(\boldsymbol{t})\big), \quad (1)$$

where $\boldsymbol{\tau} \in \boldsymbol{R^n}$ = moments of forces developed by the manipulator drives;

$\boldsymbol{M}(\boldsymbol{q}) \in \boldsymbol{R^{n\times n}}$ = manipulator inertia matrix;

$\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \in \boldsymbol{R^n}$ = matrix of coefficients taking into account centrifugal and gravitational forces, as well as Coriolis force;

$\boldsymbol{q}(\boldsymbol{t}),\ \dot{\boldsymbol{q}}(\boldsymbol{t}),\ \ddot{\boldsymbol{q}}(\boldsymbol{t})$ = position, speed and acceleration of the manipulator in the space of generalized coordinates.

Thus, the second approach is applicable when the law of motion of the manipulator along the generalized coordinates $\boldsymbol{q}(\boldsymbol{t})$ is known in explicit form. In the case of a copy type of control, the laws of generalized coordinate change are formed in the process of movement in real time [3].

The solution to this problem is to predict the movement of the operator's hand to plan the corresponding movement of the robot arm. To predict the movement of the operator hand, it is necessary to consider the time series of torque dynamic characteristics (speed, acceleration). Time series of such characteristics contain samples of too short a length for the possibility of obtaining statistically reliable forecasts most often. Therefore, the prediction of short time series is a very topical problem, to solve which it is necessary to have an idea about the features of the process described by the time series.

To predict the time series of the torque dynamic characteristics of the operator's hand motion, it is proposed to use adaptive methods. Adaptive predictive methods are able to adapt their structure and parameters to changing conditions quickly.

2. Literature review

Adaptive forecasting methods [4-6] use the temporal characteristics of parameters, the relationships of successive members of the time series, and the corresponding models are rearranged taking into account the outdated information. These models are suitable for a more accurate response to changes in members of the time series under the influence of random interference and they use corrective elements to better align the work of the main model with real data. Adaptive prediction models are based on two schemes - a moving average (CC model) and autoregression (AP model) [7,8]. In the moving average scheme, the estimate of the current level is the weighted average of all previous levels, and the weights of the observations decrease with distance from the last level, i.e. the information value of observations is recognized quicker when they are closer they are to the end of the interval of observations. Such models well reflect changes occurring in trends, but in their pure form they do not allow to reflect fluctuations. The reaction to forecast error and discounting of time series levels in models based on the CC scheme is determined using smoothing parameters (adaptation), the values of which can vary from zero to one [9,10]. In the autoregressive scheme (AP-model), the assessment of the current level is the weighted sum of not all, but several previous levels, and the weighting factors are not ranked in the observations. The information value of observations is not determined by their proximity to the modeled level, but by the tightness of the connection between them. AR-models are most suitable for stationary oscillatory processes, CC-models - for non-stationary evolutionary processes with inherent fractality properties [11,12] and multifractality [13]. The time series of the moment characteristics of the operator's arm movement are non-stationary evolutionary processes; for their prediction, we consider the CC models [14]. This article uses the updated Brown method [15], which implements the CC model using nonlinear dynamics methods (fractal analysis algorithms).

3. The developed algorithm

We will consider the work of the proposed prediction algorithm using the example of the motion law shown in figure 1. This motion law represents the experimental results $\boldsymbol{Q} = q_i, i = 1,2, \dots, n$ for capturing test motion for one of the degrees of human arm mobility taken from [16]. Motion capture results are normalized to the [0,1] range by shifting and scaling to simplify the presentation.

The developed algorithm is based on the updated Brown method [15]:

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$$\hat{q}_i = (2 - \widetilde{H})q_{i-1} - (\widetilde{H} - 1)q_{i-2}, \quad (2)$$

where $\hat{q}_i$ = estimated value;
q_{i-1} и q_{i-2} = previous known elements of the time series;
$\widetilde{H}$ – Hurst average.

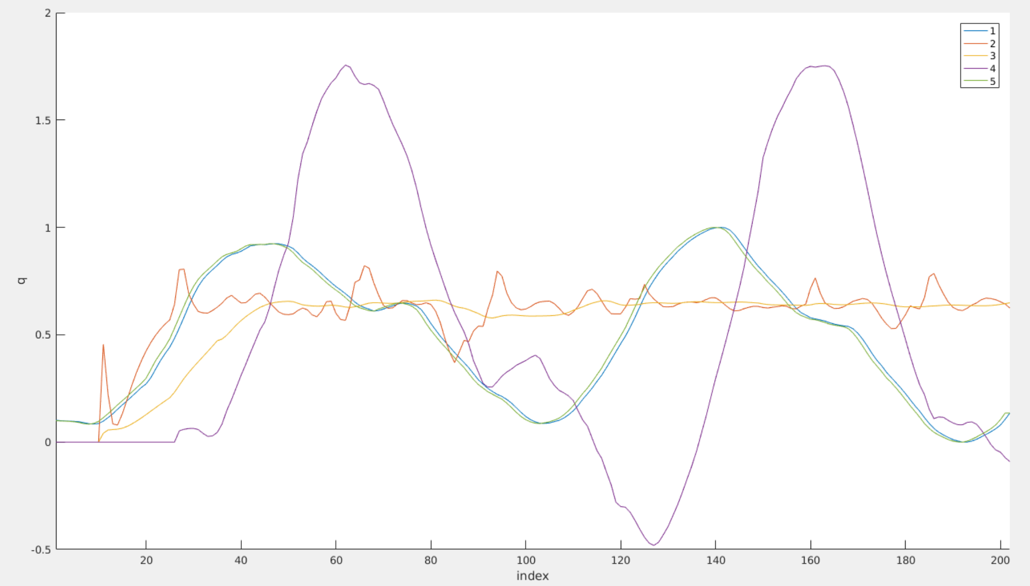

Figure 1. Simulation results: 1 – motion law; 2 – Hurst index; 3 – Hurst average; 4 – aspiration point trajectory; 5 – manipulator trajectory.

This method is intended for short-term forecasting for a forecasting distance equal to the duration of a single sampling interval of a time series. In this case, the Hurst index is calculated for all elements of the time series. The specificity of the developed algorithm is the need to predict for a longer interval, as well as the limited computing power and the need to work in real time. By virtue of these features, the algorithm uses the sliding value of the Hurst index, and the formula for calculating the forecast value takes the form:

$$\hat{q}_p = \left[(2 - \widetilde{H})q_f - (\widetilde{H} - 1)q_s\right] \cdot \frac{p - f}{f - s}, \quad (3)$$

where $\hat{q}_p$ = estimated value;
q_s = the first element included in the window for calculating the sliding value of the Hurst index;
q_f – the last element included in the window for calculating the sliding value of the Hurst index;
s – the index of the first element falling into the window;
f – the index of the last element falling into the window;
p – time series prediction index.

Another problem of the updated Brown method to be eliminated as part of the development of the forecasting algorithm is the systematic "lag" of the obtained forecast estimates from the actual values of the series. To overcome this drawback, the following change was made to formula (2):

$$\hat{q}_p = \left[q_f + \left(q_f - q_s\right)\left(1 + \widetilde{H} - < \widetilde{H} >\right)\right] \cdot \frac{p - f}{f - s}, \quad (4)$$

where $< \widetilde{H} >$ = moving average of the Hurst index.

The prediction results obtained using this method represent the "aspiration point" of the current manipulator path in the space of generalized coordinates. The forecast trajectory can be constructed using polynomial interpolation based on the known characteristics of the current position of the $q_f, \dot{q}_f, \ddot{q}_f$ manipulator and its predictive q_p.

Due to the inertia of the manipulator and regular correction, when moving along the predicted trajectory, the deviation of the manipulator from the trajectory set by the operator's hand is minimal. The results of the corresponding modeling are presented in figure 1. The average value of the deviation in the angular measure is 0.46 °.

For a comprehensive test of the effectiveness of the proposed algorithm, simulation was performed in Matlab. Since the simulation results of the operation of the algorithm strongly depend on the input data, data from [16] were used as test cases. The average value of the motion error of the manipulator based on the predicted trajectory was 0.71 ° with a standard deviation of 0.45 °.

4. Conclusion

In the course of the study, an algorithm was developed for the formation of a predictive estimate of the movement of the operator’s hand during copying control using the updated Brown method. The scientific novelty of the work consists in the development of new refinements of the Brown method, which take into account the specificity of the problem of dynamic copying control by an anthropomorphic manipulator. To assess the effectiveness of the proposed solutions, an experimental study was conducted on a simulation model. As test cases, real data obtained as a result of capturing the movements of various people when performing fixed actions with their hands were used. The experiments carried out on the simulation model showed that prediction using the refined Brown method makes it possible to realize a dynamic copying control of a manipulator with an average value of the error of following the manipulator behind the operator's hand 0.71 ° with a standard deviation of 0.45 °.

This study revealed the promising application of prediction in copy management for testing and implementation in real samples of copy control systems.

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