ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ

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Adjustable backstepping fuzzy controller for a 7 DOF anthropomorphic manipulator

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Various control methods for controlling robotic manipulators have emerged as a promising direction in the field of robotic control over the past decade. Researchers are exploring a diverse range of classical and modern techniques to address the challenging issue of time variant nonlinearities and uncertainties in manipulator dynamics. In this paper, we review and discuss several classical control methods for robotic manipulators such as model-free method,pure inverse dynamic method, andfuzzy logic-based method, to apply on a 7-degrees-of-freedom anthropomorphic manipulator. We compare and contrast the performance of these methods with oursuggested method of optimization through a series of simulation tests. An adjustable backstepping fuzzy controller is suggested, which introduces new variables into the system, where a nonlinear fuzzy filter creates a dynamic nonlinear estimator that is more robust to uncertainties, nonlinearities, and external disturbances than pure feedback linearization controllers, and decreases trial and error which makes the tuning process easier.In the suggested control law Gaussian membership functions were used instead of triangular ones.Our results demonstrate that the proposed error-based backstepping fuzzy controller can achieve high accuracy and speed, even in the presence of significant disturbances. This makes it a promising candidate for use in robotic applications where high performance is required, such as the tasks of grasping objects which is based on pattern recognition.

Keywords: fuzzy logic control, 7 DOF, time variant uncertainties, nonlinearfeedback linearization control, backstepping.

Introduction

Although classical control methods for a seven DOF manipulator position control vary from one robot model to another, three main methods can be identified: linear PID controllers, PID controllers with feed forward compensation, and nonlinear decoupling and compensation controllers. Linear PID controllers are adequate for most robotic tasks, especially in the absence of robot knowledge. They are model-free and have parameters that can be easily adjusted separately. However, linear PID controllers are joint-independent, which can lead to poor performance due to the complete elimination of manipulator dynamics. PID controllers with feed forward compensation can improve performance by accounting for known disturbances and time variant nonlinearities. However, these controllers still require a model of the manipulator, and their performance is sensitive to the accuracy of the model.

Nonlinear decoupling and compensation controllers offer the best performance, but they also require the most detailed knowledge of the manipulator dynamics.These controllers decouple the manipulator's joints and compensate for nonlinear interactions.As a result, they can achieve high accuracy and speed, even in the presence of significant disturbances. Several nonlinear decoupling and compensation controllers have been developed, some of which require a dynamical model of the manipulator and others that use adaptive control techniques to avoid the need for precise modeling. In this paper, we propose a nonlinear decoupling and compensation controller that uses a fuzzy logic back stepping controller to estimate uncertainties in the manipulator dynamics. This makes the controller partly model-free and allows it to work well in partly uncertain systems. Our results demonstrate that the proposed error-based back stepping fuzzy controller can achieve high accuracy and speed, even in the presence of significant disturbances. This makes it a promising candidate for use in robotic applications where high performance is required.

Model-free controllers

Model-free control algorithms, such as proportional-integral-derivative (PID), proportional-integral (PI), and proportional-derivative (PD), have been studied and applied quite extensively [1–3] and are widely used for robot manipulators due to their ease of implementation and tuning. However, these controllers have limitations in terms of steady-state error and transient performance.PD control guarantees stability only when the PD gains tend to infinity. However, with friction and gravity forces present in robot manipulators, the tracking error will not tend to zero.Model-based compensation is an alternative approach to PD control. This approach involves compensating for the effects of gravity and other known disturbances. However, model-based compensation requires accurate knowledge of the robot's dynamics, which can be difficult to obtain.Nonlinear PD controllers can also achieve asymptotic stability. However, these controllers are complex and have many different parameters that need to be tuned. This can be challenging, and it is not always possible to find a set of parameters that works well for all operating conditions.

In contrast to model-based compensation and nonlinear PD control, PID control is a linear controller with a simple structure. This makes it relatively easy to design and implement for controlling manipulators.To overcome the limitations of PID control, researchers have proposed a variety of feedforward compensation techniques.

Feedforward compensation involves adding a signal to the output of the PID controller to compensate for known disturbances. This signal is calculated based on thedynamic model of the manipulator and the measured disturbance.Feedforward compensation can be used to improve the steady-state error and transient performance of PID controllers. However, it is important to note that the feedforward model must be accurate in order for the compensation to be effective.Model-free control strategies for serial manipulators are based on the assumption that the joints of the manipulators are independent and the system can be decoupled into a group of single-axis control systems. This enables the design of kinematic controllers, which consist of a group of individual controllers, each for an active joint of the manipulator.

The independent joint assumption eliminates the need for a priori knowledge of robot manipulator dynamics in the kinematic controller design, simplifying the controller design and reducing the computational burden. This makes kinematic controllers suitable for real-time control applications where powerful processors are not available.However, kinematic controllers neglect joint coupling, which degrades control performance as the operating speed increases. Kinematic controllers used to control serial manipulators are only appropriate for relatively slow motion.

At high speeds, the dynamic coupling between the various robot joints increases significantly, exceeding the compensation capabilities of a standard robot controller such as PID. Therefore, model-based control is the preferred approach for serial manipulators that must operate at high speeds. The PID for serial manipulators can be expressed byEq. 1 and Eq. 2:

$$e(t) = q_d(t) - q_m(t), \quad (1)$$

where $e(t)$ is the error, $q_d(t)$ is the desired angle and $q_m(t)$ is the measured angle,

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt}, \quad (2)$$

where K_p, K_i and K_d are the controller gains.

Pure Inverse Dynamic Controller

Pure inverse dynamics control (PIDC) is a model-based feedforward nonlinear controller that is widely used in the control of robot manipulators. It is based on the feedback linearization technique, which transforms the nonlinear dynamics of the robot into a linear system. PIDC then computes the required joint torques using a nonlinear feedback control law.

This controller works very well when all dynamic and physical parameters of the robot are known.

However, in practice, most robot manipulators have unknown or time-varying parameters. In these cases, PIDC can be combined with other control techniques, such as computed torque control (CTC), to achieve robust and high-performance control. Research on PIDC has been studied and grown significantly and implemented in recent years [4] with a focus on developing new techniques to improve its robustness and performance in the presence of parameter uncertainties and disturbances.The mathematical representation of pure inverse dynamics control can be expressed by Eq. 3:

$$\tau = M(q)\ddot{q} \cdot U + B(\theta)\left[\prod_{k=2}^{N} \dot{q}_{k-1}\dot{q}_k\right] + \\ + C(q)[\dot{q}^2] + G(q), \quad (3)$$

where $M(q)$ is the mass matrix, $B(\theta)$ is the matrix of Coriolis coefficients, $C(q)$ is the matrix of centrifugal coefficients, $G(q)$ is the vector of gravity terms and q, $\dot{q}$ and $\ddot{q}$ are the angle, angular velocity and angular acceleration respectively [5], U is typically chosen as in Eq. 4:

$$U = \ddot{q}_d + K_p(q_d - q_m) + K_v(\dot{q}_d - \dot{q}_m), \quad (4)$$

and an integral term can also be added so that U will be as in Eq. 5:

$$U = \ddot{q}_d + K_p(q_d - q_m) + K_v(\dot{q}_d - \dot{q}_m) + \\ + K_i \int (q_d - q_m)\, dt, \quad (5)$$

where $e = (q_d - q_m)$which makes the dynamic error yield to Eq. 6:

$$\ddot{q}_d + K_p e + K_v \dot{e} + K_i \int e\, dt, \quad (6)$$

where K_p, $K_v$and $K_i$are the controller gains.

Fuzzy LogicControllers

Fuzzy logic controllers (FLCs) have emerged as a promising paradigm for the design of nonlinear controllers for nonlinear and uncertain systems[6, 7, 8]. Traditional control methods often require an accurate mathematical model of the system to be controlled. However, in many real-world applications, such as industrial processes, robots, and vehicles, it is difficult or impossible to obtain an accurate model.FLCs are able to overcome this challenge by using fuzzy logic to represent and reason with the uncertainty in the system.

Fuzzy logic is a mathematical framework for dealing with uncertainty and vagueness. It allows us to represent imprecise and uncertain information using fuzzy sets, which are characterized by membership degrees rather than crisp values.FLCs have emerged as a promising paradigm for the design of nonlinear controllers for nonlinear and uncertain systems.

The foundation of fuzzy logic methodology lies in the ability to represent and reason with imprecise and uncertain information.FLCs typically consist of four main components:

- Input fuzzifier: The input fuzzifier converts the numerical input signals from the system into fuzzy linguistic variables. This is done using fuzzy membership functions, which map numerical values to fuzzy membership degrees.

• Fuzzy rule base: The fuzzy rule base contains the fuzzy rules that define the relationship between the input and output fuzzy variables.

• Inference engine: The inference engine evaluates the fuzzy rules and calculates the output fuzzy variable.

• Output defuzzifier: The output defuzzifier converts the fuzzy output variable from the inference engine into a numerical output signal that can be sent to the system.

In order to address the challenge of pure inverse dynamic control (PIDC) based on time-variant nonlinear dynamic formulation, this research proposes an approach that eliminates the nonlinear equivalent formulation. This is done by replacing the dynamic nonlinear equivalent part with a performance/error-based fuzzy logic controller.

Where throughout this paper a Mamdani-type fuzzy inference system is considered,in addition to a center-of-area inference mechanism with two inputs being the error and the rate of change of the error and one output being the torque given to the system, where each of them consists of 7 sigmoid membership functions and a total of 49 rules.The center of areainference mechanism adopted in this research be can expressed as in Eq. 7:

$$\tau_{fuzzy} = \frac{\sum_{i=1}^{n} \mu(\tau_i) \cdot \tau_i}{\sum_{i=1}^{n} \mu(\tau_i)}, \quad (7)$$

where τ_i is the input to the fuzzy controller, τ_{fuzzy} are the defuzzified values, and $\mu(\tau_i)$ is the corresponding membership function as in Eq. 8:

$$\mu(\tau_i) = max[min(\mu(e), \mu(ce))]. \quad (8)$$

where e is the error and ce is the change in error.

Fuzzy Logic-Based NED Formulation Controller

In the realm of nonlinear systems, which are pervasive in the real world, control can be challenging due to the intricate dynamics and inherent uncertainties.

One approach to controlling nonlinear systems is the pure inverse dynamic control (PIDC), which entails calculating the required control input to achieve a desired system output based on the system's dynamic model.

However, PIDC can be sensitive to uncertainties in the system model. To address this challenge, a fuzzy logic-based plus gravitycan be leveraged to estimate the nonlinear equivalent dynamic formulation [9, 10, 11], as gravity can be used to estimate the nonlinear equivalent dynamic (NED) formulation in uncertain systems,given our understanding of the gravitational force and its impact on the system.

Once the NED formulation has been estimated, a fuzzy partly linear inverse dynamic controller (FPLIDC) can be designed. The FPLIDC is a parallel combination of an IDC controller and a fuzzy logic plus gravity controller. The IDC controller is responsible for controlling the linear part of the system's dynamics.

The fuzzy logic controller is responsible for compensating the nonlinear part of the system's dynamics, including the NED formulation.

This is done by the Mamdani's fuzzy inference system considerations mentioned in Eq. 7 and Eq. 8. The parallel fuzzy error-based inverse dynamic controller's output can be expressed by Eq. 9:

$$\tau = \tau_{fuzzy} + \tau_{partlylinear} + G(q), \quad (9)$$

where $\tau_{\text{partly linear}}$ is expressed in Eq. (10):

$$\tau_{partlylinear} = M(q)\begin{pmatrix} \ddot{q}_d + K_p e + K_v \dot{e} + \\ +K_i \int e\, dt \end{pmatrix}. \quad (10)$$

Adjustable Backstepping Fuzzy Controller

The proposed adjustable backstepping fuzzy controllerinspired by the work of [12–15] addresses the limitations of pure feedback linearization controllers in the presence of time variant uncertainties and external disturbances.

The fuzzy logic-based NED formulation controller approach provides a more robust solution, but calculating the controller gains is challenging.

The backstepping methodis a mathematical formulation that introduces new variables into the system that are used for feedback linearization to solve nonlinearities. In this research, a nonlinear fuzzy filter is used to create a dynamic nonlinear backstepping estimator, in the adaptive fuzzy estimator a feedback linearization process is used to eliminate or reduce the time variant uncertainties. This approach offers several advantages over existing methods.

First, the adjustable backstepping fuzzy control approach is more robust to uncertainty and external disturbances than pure feedback linearization controllers. Second, it significantly decreases the amount of trial and error which makes enables experts to tune the controller easily. Third, the proposed approach can be applied to systems with known and unknown time variant uncertainties.Where the formulation of the proposed backstepping controller can be expressed as in Eq. 11:

$$\tau = M\alpha + \beta, \quad (11)$$

where M is the mass matrix and α is the proposed control law and it can be expressed as in Eq. 12:

$$\alpha = K_1(K_1 - 1)e + (K_1 + K_2)\dot{e}, \quad (12)$$

where K_1 and K_2 are the controller gains, and β is thepartly linear term, expressed as in Eq. 13:

$$\beta = \tau_{fuzzy} + G(q). \quad (13)$$

The suggested control law is applied on a 7-DOF anthropomorphic manipulator, using Gaussian membership functions instead of triangular ones.

Results

Validation of the proposed method was conducted by implementing all the methods mentioned in this paperon a self-designed first generation 7 DOF anthropomorphic manipulator,named Hepta-GSM (Hepta - Global Serial Manipulator),with randomly selected trajectory points for each joint and comparing theresults by the help of a Matlab/Simulink simulation environment.

Two scenarios were considered: no disturbance and a band-limited white noise disturbance with a predefined 60% of the input signal power. This type of noise is suitable for modeling external disturbances in continuous and hybrid systems. The dynamics parameters of the Hepta-GSM are shown on Table 1.This manipulator will be used for grasping tasks based on object recognition mentioned in [16].

Table 1. **Dynamic description of the Hepta-GSM**

Таблица 1. **Динамическое описание Гепта-GSM**

Links	Mass, kg	Center of Mass, m
1	15.45	[0.17,0.17,0.41]
2	8.15	[0.14,0.53,0.44]
3	10.97	[0.21,0.9,0.42]
4	8.15	[0.3,1.3,0.58]
5	10.97	[0.34,1.57,0.43]
6	8.15	[0.68,1.44,0.18]
7	1.2	[0.98,1.34,0.13]

The results of comparison are shown in Fig. 1, Fig. 2, and Fig. 3, and the mean squared error under disturbance for all the joint angles of the manipulator was used as a metric for comparison as shown on Table 2.

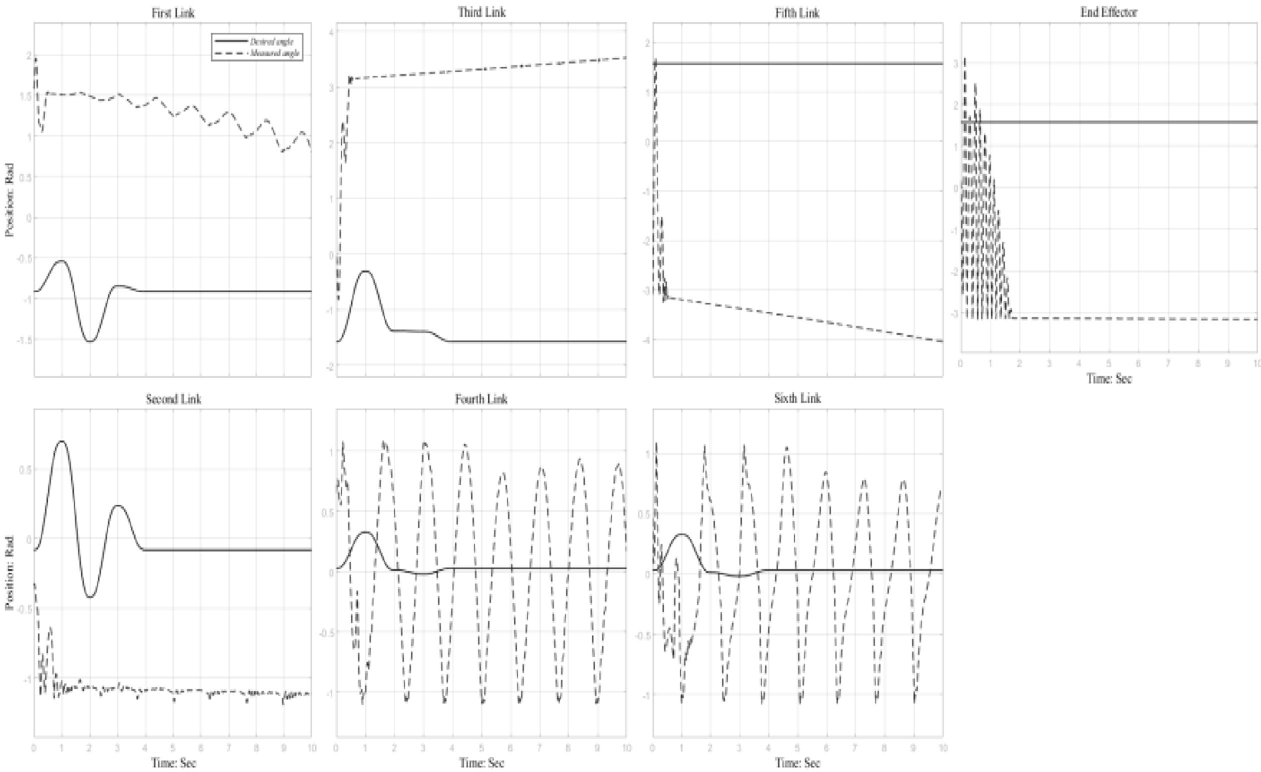

Fig. 1. Independent PID control for each joint of the manipulator

Рис. 1. Независимое ПИД-регулирование для каждого шарнира манипулятора

We can observe that the controlling of each joint independently yields instability in the joints where none of the joints followed the required path and this is due to the issue discussed earlier, which lies in the complete elimination of the robot dynamics and just considering the error in position for each joint and for this reason it will not be further mentioned in our comparison.

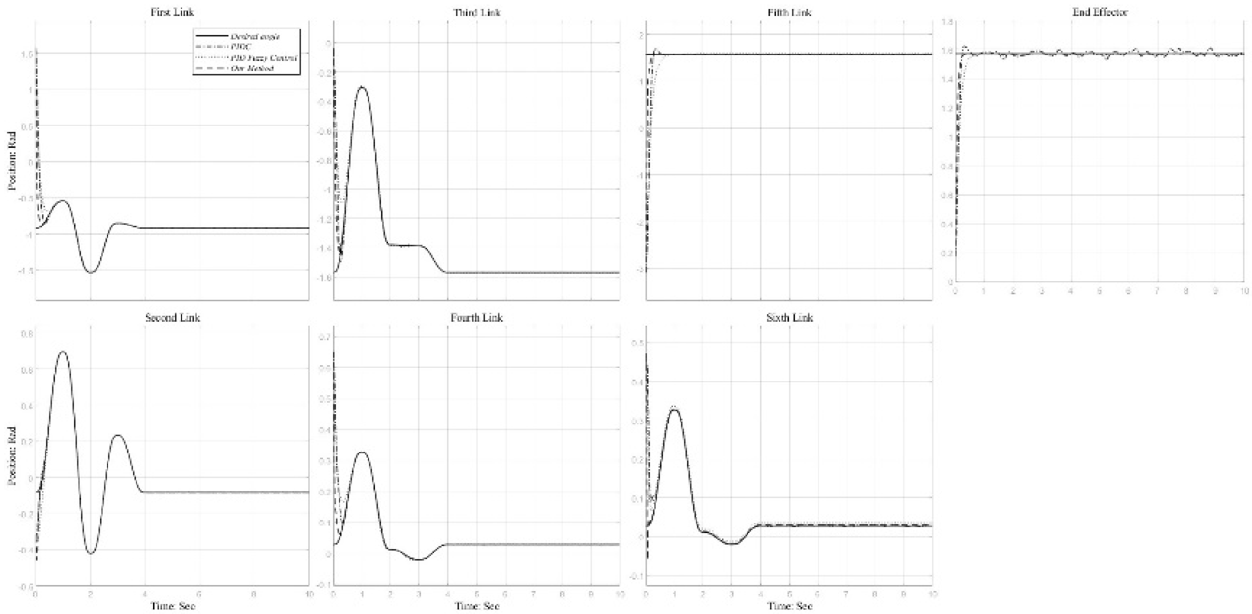

Fig. 2. Comparison of PIDC, Fuzzy PID and our method of control in case of disturbances absence

Рис. 2. Сравнение PIDC, Fuzzy PID и нашего метода управления при отсутствии возмущений

We can observe that in the case of no disturbance the Fuzzy PID and our suggested method preform very well with slightly different transient behavior and almost similar to PIDCwhich is considered to be the ideal controller in the case of no disturbances because complete knowledge of the manipulator dynamics is known and hence perfectly modeled.

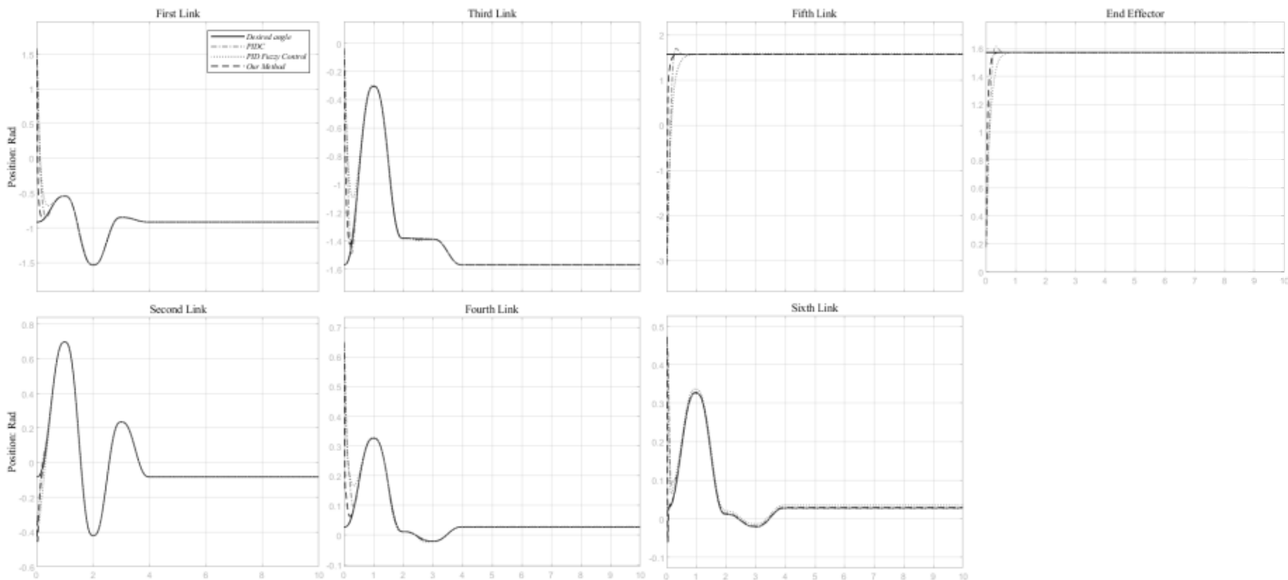

Fig. 3. Comparison of PIDC, Fuzzy PID and our method of control in case of disturbances existence

Рис. 3. Сравнение PIDC, Fuzzy PID и нашего метода управления при наличии возмущений

We can observe especially at the end effector, where the fluctuations are very clear, that the PIDC doesn't have the same consistency in performance under disturbances as it can only deal with the disturbances caused by the dynamic model but not so well with external disturbances.

On the other hand the fuzzy PID offers better performance than the PIDC but still some fluctuations are present. In our proposed method best performance is obtained where it has the best rising time and minimum overshoot and almost no oscillations are present.

Table 2. **Mean squared error underdisturbanceof joint angles**
Таблица 2. **Среднеквадратическая ошибка углов при возмущении на сустав**

Method	Error	q_1	q_2	q_3	q_4	q_5	q_6	q_7
PIDC	MSE	0.3496	0.0365	0.2214	0.0873	0.6599	0.0622	0.1945
PID Fuzzy control	MSE	0.3015	0.0439	0.1962	0.0730	0.5737	0.0498	0.1694
Our Method	MSE	0.2462	0.0466	0.1625	0.0574	0.4470	0.0432	0.1428

Conclusion and Discussion

The proposed controller was evaluated on a 7 DOF anthropomorphic manipulator with a variety of uncertainties, and the results showed that it outperformed other control methods, such as pure inverse dynamic control and fuzzy logic-based nonlinear equivalent dynamic control. The proposed controller was able to achieve accurate tracking performance, lowest error in joints, and it reduces output oscillation even in the presence of significant uncertainties.Our contribution lies in that the suggested control law is applied for the first time on a 7-DOF manipulator, a part from using Gaussian membership functions instead of triangular ones, as they are nonlinear by nature, and more suitable to deal with nonlinearities present in the system.This work provides a general guideline for future research in selecting the appropriate control methods for robotic manipulators.

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Регулируемый нечеткий контроллер обратного хода для антропоморфного манипулятора с 7-степенной свободой

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За последнее десятилетие различные методы управления роботизированными манипуляторами стали многообещающим направлением в области роботизированного управления. Исследователи изучают широкий спектр классических и современных методов для решения сложной проблемы вариативных нелинейностей во времени и неопределенностей в динамике манипулятора. В этой статье мы рассматриваем и обсуждаем несколько классических методов управления роботизированными манипуляторами, таких как метод регулирования без использования модели, метод регулирования с чистой обратной динамикой, метод регулирования нелинейных эквивалентных динамических формулировок на основе нечеткой логики, которые можно применить к антропоморфному манипулятору с 7 степенями свободы. Мы сравниваем эффективность этих методов с предложенным нами методом оптимизации с помощью серии имитационных тестов. Предлагается регулируемый нечеткий контроллер с обратной связью, который вводит новые переменные в систему, где нелинейный нечеткий фильтр создает динамическую нелинейную оценку, которая более устойчива к неопределенностям, нелинейностям и внешним возмущениям, чем контроллеры с линеаризацией с чистой обратной связью, и уменьшает количество проб и ошибок, что упрощает процесс настройки. В предложенном законе управления вместо треугольных функций принадлежности использовались гауссовы. Наши результаты демонстрируют, что предложенный нечеткий контроллер с обратным шагом, основанный на ошибках, может достигать высокой точности и быстродействия даже при наличии значительных помех. Это делает его многообещающим кандидатом для использования в роботизированных приложениях, где требуется высокая производительность, такие как задачи захвата объектов, основанные на распознавании образов.

Ключевые слова: нечеткое логическое управление, 7 степеней свободы, временные вариантные неопределенности, нелинейное линеаризационное управление с обратной связью, обратный шаг.

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