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ADAPTIVE CONTROL OF ROBOT MANIPULATORS – A BRIEF REVIEW OF RECENT ADVANCES

РОБОТ-МАНИПУЛЯТОРЛАРДЫ БЕЙІМДЕЛМЕ БАСҚАРУ – СОҢҒЫ ЖЕТІСТІКТЕРГЕ ҚЫСҚА ШОЛУ

АДАПТИВНОЕ УПРАВЛЕНИЕ РОБОТАМИ-МАНИПУЛЯТОРАМИ – КРАТКИЙ ОБЗОР ПОСЛЕДНИХ ДОСТИЖЕНИЙ

Abstract. *Currently, there is a rapid development of various industries using robotic manipulators. Robotic manipulators are controlled by programmable controllers. Most industrial controllers use a common control principle, namely, a linear proportional control algorithm for each link, where the spatial position of the working tool is corrected, and the position of the tool is a feedback signal. This method is suitable for low speeds and requires movement along a given trajectory in time. However, the development of modern robotic production requires more flexible, adaptive control of the production process in order to increase the speed of passing a given trajectory and set the trajectory without preliminary calculations for each individual link of the robot. A large amount of the research is currently devoted to the solution of this problem all over the world, but the solution is ambiguous and varies in relation to the control of specific processes. This review presents a brief description of the principles of adaptive control and discusses the results of recent research in this area in relation to the control of robotic manipulators. Recent advances in adaptive control systems for robotic arms in terms of their applications are reviewed with critical comments on related issues. It is expected that the wide dissemination of this review will stimulate closer collaboration between industry and the research community and encourage further developments.*

Keywords: *Adaptive control, robotic manipulators, programmable controllers, technological applications*

Аңдатпа. *Қазіргі уақытта робот-манипуляторларды қолданатын түрлі өндірістердің қарқынды дамуы жүріп жатыр. Робот-манипуляторлар бағдарламаланатын контроллерлер арқылы басқарылады. Өнеркәсіптік контроллерлердің көпшілігі басқарудың жалпы принципін қолданады, атап айтқанда жұмыс құралының кеңістіктік орналасуы реттелетін әр буын үшін пропорционалды басқарудың сызықтық алгоритмі, ал кері байланыс сигналы бұл құралдың орналасуы болып табылады. Бұл әдіс төмен қозғалыс жылдамдығына жарамды және белгілі бір* *траектория арқылы қозғалысты уақыт бойынша жүргізуді талап етеді. Алайда, қазіргі заманғы роботтандырылған өндірістерді дамыту берілген траекторияның өту жылдамдығын арттыруды және роботтың әрбір жеке буыны үшін алдын ала есептеусіз траекторияны белгілеу үшін өндірістік процесті неғұрлым икемді, бейімделме басқаруды талап етеді. Қазіргі уақытта бүкіл әлемде көптеген зерттеулер осы мәселені шешуге арналған, бірақ шешім анық емес және белгілі бір процестерді бақылауға қатысты өзгеріп отырады. Бұл шолуда бейімделме басқару принциптерінің қысқаша сипаттамасы берілген және робот-манипуляторларды басқаруға қатысты осы саладағы соңғы зерттеулердің нәтижелері қарастырылған. Робот-манипуляторларды бейімделген басқару жүйелеріндегі олардың қосымшалары тұрғысынан соңғы жетістіктер олармен байланысты мәселелер бойынша сыни пікірлермен қарастырылады. Бұл шолудың кең таралуы өнеркәсіп пен ғылыми-зерттеу қоғамдастығы арасындағы тығыз ынтымақтастықты ынталандырады және одан әрі дамуға ықпал етеді деп күтілуде.*

Түйін сөздер: *Бейімделме басқару, робот-манипуляторлар, бағдарламаланатын контроллерлер, технологиялық қосымшалар.*

Аннотация. *В настоящее время происходит стремительное развитие различных производств, использующих роботы-манипуляторы. Роботы-манипуляторы управляются при помощи программируемых контроллеров. Большая часть промышленных контроллеров использует общий принцип управления, а именно: линейный алгоритм пропорционального управления для каждого звена, где корректируется пространственное положение рабочего инструмента, а сигналом обратной связи является положение инструмента. Такой метод пригоден для низких скоростей движения и требует осуществлять движение по заданной траектории во времени. Однако, развитие современных роботизированных производств требует более гибкого, адаптивного управления производственным процессом, чтобы увеличить скорость прохождения заданной траектории и задать траекторию без предварительных расчетов для каждого отдельного звена робота. Решению этой проблемы в настоящее время во всем мире посвящено большое количество исследований, но решение неоднозначно и варьируется применительно к контролю конкретными процессами. В этом обзоре даётся краткое описание принципов адаптивного управления и рассматриваются результаты последних исследований в этой области применительно к управлению роботами- манипуляторами. Последние достижения в адаптивных системах управления роботами-манипуляторами с точки зрения их приложений рассматриваются с критическими комментариями по связанным с ними проблемам. Ожидается, что широкое распространение этого обзора будет стимулировать более тесное сотрудничество между промышленностью и исследовательским сообществом и способствовать дальнейшим разработкам.*

Ключевые слова: *Адаптивное управление, робот-манипулятор, программируемые контроллеры, технологические приложения.*

Introduction. Currently, the development of new control algorithms of multilink robotic manipulator is in the focus of the world scientific research representing significant scientific and practical interest in relation to specific technological processes.

The purpose of this review article is a critical analysis of modern research in the field of adaptive control of robotic manipulators in order to present the latest achievements in this field and the challenges associated with the prospects of the industrial implementation of adaptive control. It is expected that this review will stimulate closer cooperation between researchers of various fields, including using and control of robotic manipulators, as well as contribute to further developments for implantation into manufacturing.

For the analysis, reliable open information sources of information were used, including mainly research articles in peer-reviewed scientific journals or proceedings of prestigious scientific conferences over the past 5 years.

Literary review. The robotic manipulator has become an integral part of modern industrial automation. Currently, the use of the robotic manipulators in industry is steadily expanding, robots are used for coating, loading and packaging operations, on assembling conveyers of automotive and machinery manufacturing plants, etc., since their characteristics allow the technological process to be carried out with precision accuracy and high productivity. It is also important that industrial automation with the help of robotic manipulators allows for long-term technological processes in difficult or harmful conditions for humans, without direct human involvement.

Currently, due to automation of thermal plasma spraying processes, it has become possible to apply these technologies for additive manufacturing of multilayer functional coatings [1-4]. This is a very promising direction that allows to obtain layer upon layer of coatings for medicine [1, 2] or electronics [3, 4] with the desired composition and microstructure along a given 3D-model of the product.

At the same time, a number of challenges still exist for the implementation of thermal plasma spraying technology directly into additive coatings industry. Including the challenge which has focused the attention by a number of researchers in the field of automation and robotics, remains such a control of the robotic manipulator, which would allow for fast and accurate movement of a working tool (for example, a plasmatron) along the given 3D trajectory[5-8], that is necessary for the additive coating manufacturing.

Robotic manipulators are controlled by programmable controllers. Most industrial controllers use a common control principle, namely, a linear proportional control algorithm for each link, where the spatial position of the working tool is corrected, and the position of the tool is the feedback signal. This method is suitable for low speeds and requires movement along a given trajectory in time. However, the development of modern robotic production requires more flexible, adaptive control of the production process in order to increase the speed of passing a given trajectory and set a trajectory without preliminary calculations for each individual link of the robot. A large amount of research is currently devoted to the solution of this problem all over the world, but the solution is ambiguous and varies in relation to the control of specific processes.

This review presents a brief description of the principles of adaptive control and discusses the results of recent research in this area in relation to the control of robotic manipulators.

Adaptive control is able to adapt to a controlled system with parameters that are constantly changing or initially unknown. If the control system relies on a posteriori data, for example, the control system parameters change due to changes in the system parameters or due to interference from the environment, then this control system is called adaptive. As for the non-adaptive control system, the control system is modeled on the basis of a priori system data, in other words, the system and the controller being developed are known, intended only for this system, and it is assumed that the changing phenomenon does not exist inside the system. In other situations, when it is not known how the operating state of the system will change, it is necessary to plan changes in parameters within the control system. Thus, using the example of aircraft movement control, it is clear that when designing the aircraft control system, its speed and altitude must be taken into account, and it is expected that the aircraft will move at certain values of altitude and speed at each point of the trajectory. In this situation, the controller of the control system can be designed for each individual expected working point of the trajectory, and different controllers can be replaced by each other, this is called gain planning. In other scenarios, when the system parameters change, but the degree of parameter change is also known, in this situation it is possible to develop a fixed controller that is able to handle various parameter changes and provide reliable control.

Cheng et al. [9, 10], Na et al. [11], C. Yang et al. [12] independently developed adaptive control algorithms for robotic manipulators, generically described as follows: the desired path determines the ideal response of the controlled system; a numerical model describes the dynamics of the robot and its interaction with the environment; a well-designed controller is used to generate appropriate control signals to actuate the drives to create the required torques. Thus, the robotic manipulator can follow the desired trajectory.

According to Zhang and Wei (2017), adaptive control can be divided into three types: MRAC (Model Reference Adaptive Control), self-tuning control and gain control [13]. As for MRAC, input data is entered into the real and reference systems, and an error is generated between the real output and the output of the reference model. The error is then used to change the controller parameters to minimize the error. The scheme of the reference model of adaptive control is shown in Figure 1.

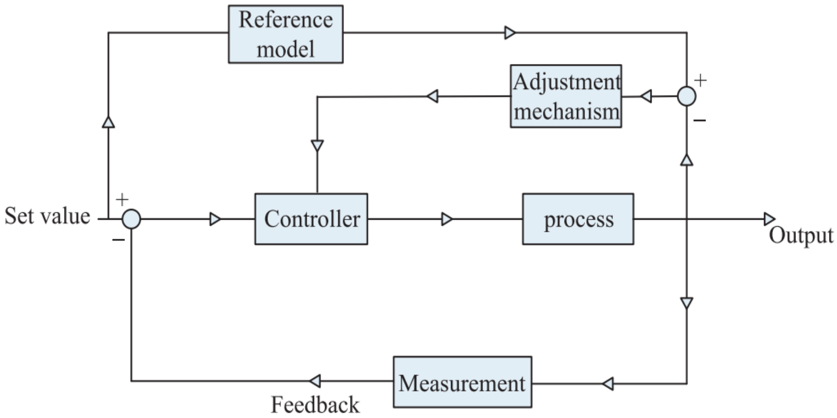

Figure 1. Reference model of an adaptive control system [13]

Wang (2017) investigated the problem of adaptive control of the robotic manipulators with both the kinematic and dynamic uncertainties [14] and proposed two adaptive control schemes with controllers to implement the task of tracking the trajectory in the task space regardless of the kinematic and dynamic uncertainties. It was assumed that the certain sensors in the task space (for example, a camera) are used to provide information about the position/velocity in the task space in the case when the kinematic parameters are unknown. The designs of adaptive controllers for the robotic manipulator and the purpose of the control were to force the robot's final effector to asymptotically track the desired trajectory in the task space. The adaptive controller had the separation property and used the law of adaptation of the joint reference speed and kinematic parameter. The performance of the proposed controllers was shown by numerical modeling. It was shown that the proposed controllers also had the desired separation property, that the first adaptive controller (with appropriate modifications) could provide improved performance without the cost of conservative gain selection, and also that to obtain potentially good tracking performance in the task space, adaptive Jacobian feedback seems preferable than the commonly used adaptive transposed Jacobian feedback.

The advantage of the adaptive control schemes proposed by Wang [14] is that the separation of kinematic and dynamic contours is more suitable for use in industrial robots. The reason for this is that the kinematic control law (represented by the joint speed reference) in combination with the kinematic parameter adaptation law ensures that tracking errors converge in task space as long as the combined servo loop (typically built into most industrial robots) can ensure that the joint speed approaches the reference joint velocity fairly quickly, in the sense that the joint velocity tracking error is integrable over the square of its magnitude and limited.

Perumal and Natarajan (2017) also used the kinematic and dynamic loop separation property to control a three-link rigid robotic manipulator using the hardware-in-the-loop (HIL) modeling method [15]. The solution was presented by implementing two different adaptive control schemes in order to track the trajectory of the end effector of the robotic manipulator in the task space. Both proposed regulators were developed taking into account the joint reference speeds and the additional separation property. Based on this, the controllers were called adaptive reference velocity (RV) controllers and reference velocity separation (RVS) controllers, respectively. Two developed adaptive control schemes, RV and RVS, were implemented using the C2000 real-time controller, and HIL modeling was performed using MATLAB 2012b and Code Composer Studio 5. The above adaptive control was implemented to actuate a three-link planar rigid robotic manipulator that captures an unknown object. The adaptive control described above was implemented to actuate a three-link flat rigid robotic manipulator that captures an unknown object. From the simulation results [15] it followed that the adaptive RV controller provided better tracking accuracy by about 0.0015 m at t = 6 s and more adequate use of joint torques. The accuracy of tracking in the loop by the adaptive RVS controller after t = 6c was similar; therefore, the dynamics of the closed loop approached linear dynamics with critical attenuation. From the experimental results implemented by HIL, it followed that the developed adaptive RV controller has better trajectory tracking accuracy with minimal torque, and the adaptive RVS controller responds better to joint tracking errors and converges faster [15].

Control of high-precision robotic manipulators capable of moving at high speeds places high demands on the robot controller. Positioning of such robots is a nonlinear task, since the mathematical model of the manipulator includes coordinate transformation matrices having sine and cosine terms. Linear manipulator control assumes that each joint is independent and takes into account the moments of inertia "visible" by the drive controllers of each joint as constants. This approximation leads to a number of undesirable effects. Let's take a closer look at the proposed approaches to adaptive control of robotic manipulators, allowing us to avoid such disadvantages.

Ali et al. (2021) developed an adaptive robust control algorithm using a sliding control mode (SMC) and Lugre friction model to control the movement of the robotic manipulator along the required trajectory, and Lyapunov approach was proposed for the stability of the system [16]. The negative aspect of the proposed approach with friction compensation is that the temperature effect on the parameters and operation of the robot joints is not taken into account, and also that large values of control coefficients have to be introduced to solve vibration problems. In practice, the robot's joints heat up due to friction after the manipulator has been working for some time, and the robot can also be operated at low or high temperatures, so temperature effects must be taken into account.

Chen et al. (2016) noted that adaptive control for tracking the trajectory of robotic systems with uncertain kinematics and dynamics is usually based on the assumption that uncertainties can be expressed in the form of linear parametrization [17]. In this sense, the above methods are basically model-based control. Although theoretically they can provide satisfactory control characteristics, the requirements for an accurate mathematical model limit their application [17]. Moreover, in most conventional adaptive control schemes, it is assumed that joint acceleration signals are available for controller design [13]. However, the measurement of joint accelerations is practically impractical, since it is usually sensitive to external interference and noise. To ease the requirements for knowledge of the robot model, neural networks (NNs) can be used as an effective tool for approximating nonlinear uncertainties.

Yang et al. (2018) proposed adaptive neural control based on a neural network with a radial basis function (RBFNN) for robotic manipulators to achieve guaranteed monitoring and estimation of tracking [18]. Since the measurement of joint accelerations is sensitive to external noise, the authors [18] avoided the direct use of acceleration signals by reformulating the robotic model. This consisted in the fact that first two auxiliary variables were developed for the reconstruction of the robotic model, then a low-pass filter was applied to the reformulated model in such a way that when developing adaptive control laws, it was possible to avoid taking into account the joint acceleration. RBFNN has been used to approximate concentrated unknown nonlinear dynamics in order to weaken the system knowledge requirement. In order to preserve the convergence of control and estimation, the adaptive parameter estimation proposed earlier (2015) by Na et al. [11], was additionally adapted and included in the adaptive design of neural control. Thus, both the tracking error and the weight estimation error NN were used in the new adaptive control law, and thus the convergence of the tracking error and the weight estimation error could be guaranteed simultaneously. To demonstrate the effectiveness of the proposed methods, the authors [18] presented numerical simulation based on the robot SCARA 2-DOF.

When designing controllers for robotic systems, methods such as the disturbance observer method, the adaptive neural network control, the fuzzy logic control, the feedback linearization approach and the slide model control method do not take into account external factors such as input dead zone, saturation and backlash. These non-linearities exist in robotic actuators, and it is quite difficult to obtain their exact models. Ignoring these non-linearities in order to simplify the control design can lead to a decrease in productivity and control efficiency. Therefore, recently researchers have been using neural networks with new structures based on Wavelet neural networks (WNN) [13, 19-21] or solving nonlinear problems with an input dead zone [22]. The ability of WNN to learn when identifying systems is higher than that of conventional neural networks, since the wavelet functions are localized in space. The WN learning algorithm has a shorter convergence time than that of a conventional neural network, and the control of a controller developed on the basis of WNN is more efficient [13, 19-21].

Tomczyk et al. (2019) successfully applied WNN to approximate unknown functions and unknown feedback in transformed systems [21].

Sun et al. (2020) proposed an adaptive WNN control method for the robotic manipulator with an input dead zone [22]. The new adaptive WNN controller was designed to achieve the output trajectory using the backstepping method. WNNs were used to approximate the virtual control laws generated in the backstep control procedure and the unknown nonlinear function of the system.

Ahmed et al. (2019) presented H∞-adaptive tracking control of an uncertain robotic manipulator with unknown external disturbances and input time-varying delays [23]. Proposed by Ahmed et al. the control scheme (Figure 2) is used to ensure that the position of the hinges provides accurate tracking of the desired trajectory for the robotic manipulator with n-degrees of freedom.

As can be seen in Fig.2, where r is bounded reference input vector, x is state vector, x_r is known matrix, e is tracking error $(x- x_r)$, ω is unknown bounded input acting on the manipulator, τ are control input torques applied to the manipulator, K is a constant gain matrix, $d(t)$ - continuous and time-varying function satisfying $0 \leq d \leq \eta$ (η is known positive scalar), $\theta, \dot{\theta}$ are joint position and velocity, $\widehat{M}$ is the estimate of inertia matrix M, $H(\theta, \dot{\theta})$ is the matrix of centripetal forces and coriolis forces, $G(\theta)$ is the matrix of gravitational forces, such the H∞ adaptive controller can be proposed to develop a reliable time-delay controller with non-smooth nonlinearities such as saturation and dead zone.

It should also be noted that parametric uncertainties caused by environmental influences and safety problems associated with the physical interaction of a human and a robot are inevitable in robotic systems. To perform the specified tasks in real applications, undefined robotic manipulators must work taking into account both safety and performance requirements. Control strategies that partially focus on performance without security guarantees often lead to a lack of practicality and vice versa [13, 24]. These challenges motivate researchers to develop an effective strategy for robotic manipulators control in such a way that safety, performance and uncertainty can be considered together.

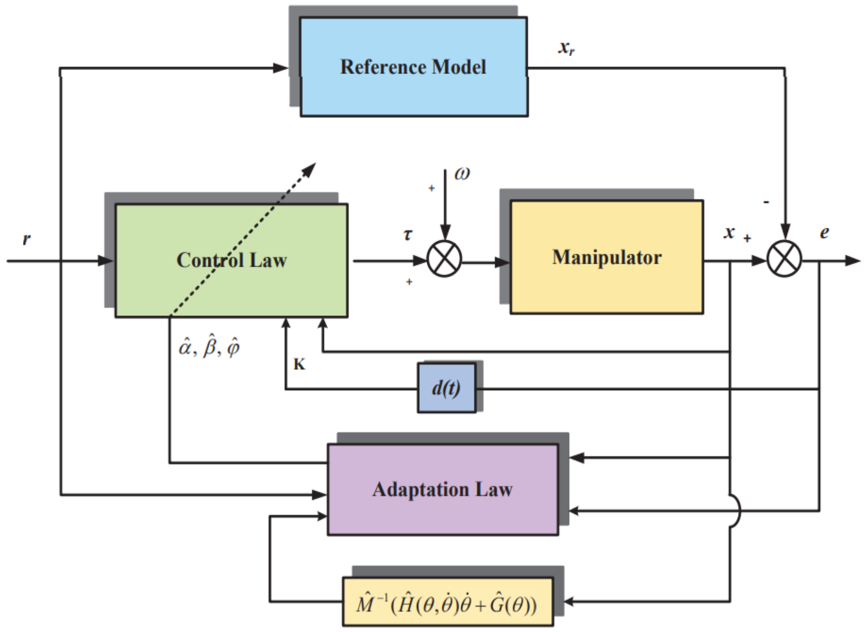

Figure 2. Scheme of the H∞-adaptive tracking control model [23]

For example, Song et al. (2021) developed an adaptive control strategy, schematically presented in Figure 3 [24], where $\hat{\theta}$ is the estimated parameter vector, y is the output state, y_d is the desired trajectory, y_f is the filtered version of y, u is the system output, u_f is the filtered version of u, e is the trajectory error.

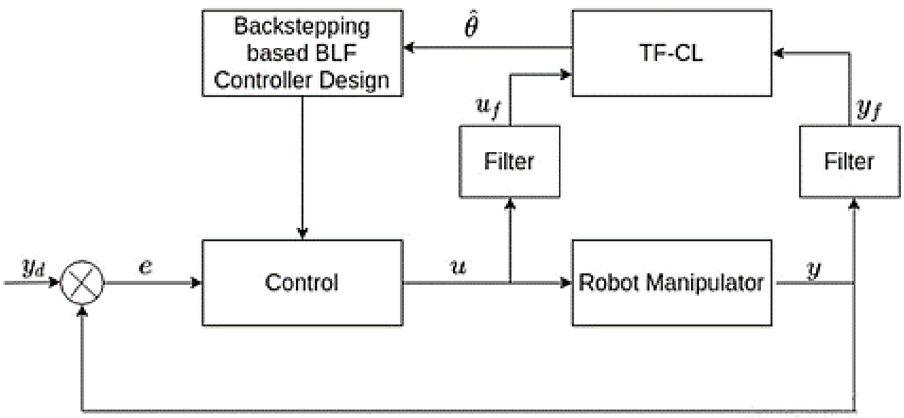

Figure 3. Scheme of adaptive control of a partially indeterminate robotic arm. [24]

The proposed scheme of adaptive control of a partially indeterminate robotic arm (Fig. 3) can simultaneously solve the following issues:

1) security issues in terms of output constraints;

2) guaranteed performance against tracking errors;

3) parametric uncertainties of a partially unknown robotic manipulator.

This adaptive control strategy for tracking an undefined n-link robotic manipulator with guaranteed safety and performance is based on ABLF (asymmetric barrier Lyapunov function), TF-CL (torque filtering-concurrent learning) and backstepping methods [24]. The TCL-based parameter estimation update law ensures that without the inclusion of external noise to satisfy the PE (persistence of excitement) condition, the estimated parameters quickly converge to the desired values. Information about the acceleration of joints is excluded using the torque filtering method. Based on the computational model, the proposed control strategy can force an indefinite n-link robotic manipulator to effectively track the desired trajectory, while meeting safety and performance requirements. It was proved that the output data of the system always remains in a given safety set, the tracking error is bounded by the performance set, and the parameter estimation error eventually converges asymptotically to 0 [24]. This method has practicality compared to conventional methods, which must include external noise to satisfy the excitation retention condition for parameter convergence.

It should be noted that Kazakhstani scientists are also successfully work in this promising direction, in particular Shadrin et al. (2019-2020) developed the method of Correction Dynamics and Perturbations Compensation (CDPC) and successfully applied it to adaptive control of an industrial robotic manipulator with 6 degrees of freedom performing microplasma spraying operations of functional coatings on the surface complex shape [6, 25]. Based on the consideration of the features of the manipulation robot, the task of control its movement in one direction was considered as control of a second-order linear object. Application of the CDPC method made it possible to obtain the control algorithm such a general object in an analytical form by means of algebraic operations on matrices, as well as to obtain an algorithm for controlling the angle of rotation of a link of the robotic manipulator. The initial data for the calculation of the control system were the mathematical model of the control object and the free parameters of the reference filters, which was convenient for practical applications. The algorithm provided zero static error and testing of external influences with the accuracy of standard filters. Application of Vyshnegradsky form facilitated the parametric identification of the object and the setting of the free coefficients of the reference filter, which are convenient in relation to the description of the robot's movement. The analysis of the robot motion control system in the simulator program allowed to conclude that the system provides the specified quality indicators and has the properties of parametric and structural robustness.

Results and Discussion. Thus, the results of the analysis of modern research methods of the robotic manipulator control show that although linear control has been successfully used for decades, but it may not be able to service modern and advanced technologies using robotic manipulators with several degrees of freedom, for which adaptive control is a necessity. However, there is a number of challenges associated with the use of adaptive control of such robots and the decision to choose linear or adaptive control for a particular application can be difficult. The fact is that linear control is well tested and proven for industrial applications. Many excellent analysis tools are available for linear systems, such as Nyquist stability criteria, Laplace transform, Z-transform and Fourier transform, etc., whereas adaptive control of a nonlinear system may require complex mathematical analysis using methods such as, for example, Lyapunov stability criterion, Popov criterion, singular perturbation methods. Mathematical modeling can also be cumbersome for nonlinear systems. A nonlinear system can be subject to chaotic disturbances and bifurcations. Most schemes of nonlinear systems can provide only local stability, while full stability can not be guaranteed [26]. Despite the fact that the saturation of the actuator usually occurs with linear control, it can be more problematic and even catastrophic in the case of nonlinear control, since the control signal here is very powerful and aggressive. Consequently, it is easily leads to system hang. In order to have deal with the problems of drive saturation, an emergency compensator can be included in the reference model of adaptive control of a robotic arm, but the emergency compensators usually worsen the operation of the control circuit [26].

For the above reasons, there are difficulties in the industrial implementation of adaptive control of robotic manipulators. The industry still relies mainly on simple traditional linear circuits. Additional work is needed to reduce the complexity of advanced adaptive control strategies and make them more attractive for industrial implementation. Considerable efforts are needed to develop reliable and fairly easy-to-implement adaptive control algorithms in order to convince manufacturing engineer (control specialists) to apply modern methods of adaptive control for the needs of industry.

Conclusion. The review of modern literature has shown the growing needs of industries using robotic manipulators in the application of adaptive approaches to their control. This review briefly describes the main modern approaches and methods of implementing adaptive control of multi-link manipulators, as well as the article shows the main advantages and challenges associated with the application and industrial implementation of modern advanced methods of adaptive control of robotic manipulators. This review encourages closer cooperation between researchers in various fields, including the use and control of robotic manipulators, and can also contribute to further developments for implementation in production.

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