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TRENDS AND KEY TECHNOLOGIES IN ADAPTIVE ROBOT CONTROL

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Abstract

This article explores the current trends and enabling technologies in the field of adaptive control for robotic systems. It discusses the shift toward intelligent, learning-based approaches, the integration of artificial intelligence, and the emergence of hybrid control architectures. Key technologies that support reliable robot behavior in uncertain and dynamic environments are presented. The paper also outlines future prospects and challenges for research and implementation.

1. Introduction

Modern robotic systems are faced with the need to operate in complex, unstable and uncertain conditions. Classical management approaches based on static models lose their effectiveness in dynamic and unpredictable environments. In this regard, adaptive control is of particular importance, providing a modification of the robot's behavior strategy based on current data and changing conditions.

In the modern world, robotics has become one of the leading areas of scientific and technical achievements, and these technologies are widely used in industrial automation, space exploration, medicine, everyday life, housing and communal services, environmental monitoring, ensuring the safety of facilities, and military affairs. Robots designed to perform a variety of tasks are used in many areas. However, in the development and production of robots, effective interaction with variable and non-standard environments remains one of the most complex and pressing problems. Adaptive robot control systems are a new generation of technologies that can cope with dynamic and uncertain environmental conditions.

Adaptive robot control systems are systems that can change their behavior and control parameters depending on changes in the external environment or internal conditions to ensure reliable execution of assigned tasks. Unlike classical control methods, adaptive systems are based on the principles of learning and prediction, which allows robots to quickly adapt to changing circumstances and solve problems more effectively.

According to the functional purpose of the robot itself, these systems can be divided into adaptive control systems for manipulation and mobile robots. The most important features for classifying the adaptive control systems under consideration are the characteristics of the sensor devices used. According to the modeling of biosensor functions, technical sensors can be classified into visual, auditory, tactile and kinesthetic.

Visual sensors provide remote information on geometric and, possibly, some physical characteristics of the external environment (color, soil properties). There are a large number of technical means that can be used to solve this problem: television systems of various types, optical-electronic devices with charge coupling and photodiode matrices and rulers, various location devices.

Auditory (acoustic) sensors are designed to perceive sound vibrations and identify the corresponding acoustic image based on them. Sound devices are important for organizing speech communication between a human operator and a robot.

Tactile sensors allow you to record contact with objects in the external environment. They are widely used to sense the grip of a manipulator and a robot body.

Kinesthetic sensors in living organisms form a muscular sense that allows information to be obtained about the position of individual organs and the forces in them.

II. Main part

The development trend is based on achievements in robotics such as increased autonomy, where modern robots are becoming increasingly independent in decision-making. Adaptation is carried out not only at the level of motion trajectories, but also at the level of behavioral strategies. The autonomy of robots and, consequently, the suitability of their use in a familiar human environment, as well as in extreme environments when solving a wide range of applied problems, taking into account existing spatial, temporal, information and energy limitations, consists of basic components such as a combination of mass-dimensional and design parameters, advanced hardware, intelligent information and control system and energy reserves. When solving various applied problems, robots have certain combinations of mass-dimensional and design parameters, as well as advanced hardware, including powerful engines and high-precision sensors for perceiving primary information about the external environment. Thus, until recently, the emphasis in the development of mobile robots for various purposes was shifted towards the use of wheeled platforms, but recently close attention of the world scientific community has been drawn to walking robotic structures [Cully et al., 2014, p. 1] and multirotor aircraft [Hehn, D'Andrea, 2011, p. 1485], which have an order of magnitude greater capabilities for movement in space. Also, the organization of the expedient behavior of autonomous robots is unthinkable without an intelligent information and control system that solves the problems of analyzing the external environment, as well as generating commands for the robot to move and manipulate nearby objects. An important component of the autonomy of a robotic system is the availability of a sufficient supply of energy. In comparison with a person, modern robots lose in this criterion in most cases. Thus, a person can do without food for up to several days, restoring their performance in a matter of minutes after eating. At the same time, the batteries of robots comparable in size to a person provide uninterrupted operation only for a few hours and significantly lag behind a person in terms of charge recovery time.

The use of reinforcement learning algorithms allows robots to learn strategies for interacting with the environment based on rewards for successful actions. With the help of reinforcement learning, robots are taught complex manipulations, such as putting goods into boxes in warehouses. Adaptive movement strategies are developed for drones and walking robots, and industrial processes are built without stopping production. The main task of adaptive control is to create robots that are capable of not only independently perceiving and analyzing information from the environment, but also adjusting their behavior based on the data received. This requires the ability to model and predict the dynamics of the system, interact with variable and noisy signals, and adequately respond to unexpected situations.

Adaptive industrial robots with artificial intelligence must meet the following basic requirements:

1. Form a goal. In this case, the target information must be perceived through the operator's direct speech, as well as through any media used.

2. A robot capable of significantly increasing the degree of automation of production must have great kinetic freedom, ensuring significant flexibility of action in various working conditions, when performing various tasks, with different shapes and different relative locations of processed objects, all kinds of obstacles, etc.

This dictates the need to equip such robots with multi-link manipulators with a large number of programmable degrees of mobility of the main (local and regional) movements (6-8 or more), as well as equipping them with a set of gripping devices and tools with the ability to quickly and automatically change. It is promising to equip an integral robot with two or more manipulators and anthropomorphic gripping devices.

3. Recognize the environment, for which the robot must be equipped with developed and diverse systems of external and internal information about the state of the environment and the state of the robot's mechanisms and systems. These must be sensors of various functional purposes and designs (visual, tactile, force, force-torque, pressure, temperature, etc.). The interaction of external and internal information sensors must also ensure the functioning of the robot's own safety system.

4. Adapt to changes in the environment and actively interact with it to achieve the set goal.

5. The robot's intellectual abilities must include a certain degree of awareness of the environment, the ability to assess changes occurring in the surrounding conditions, and the ability to learn based on accumulated experience.

This paper employs a comparative-analytical approach to examine key adaptive control strategies in robotics. The following sources and methods were used:

Literature Review: Over 30 peer-reviewed articles, books, and industrial whitepapers were reviewed (e.g., Sutton & Barto, Siciliano & Khatib).

Classification: Technologies were categorized based on architecture (e.g., neural vs. model-based), adaptability level, and application domain.

Visualization: Graphical representation of technological impact was created to compare relevance across domains.

III. Results

The main key factors of adaptive control that ensure successful interaction of robots with variable and complex environments are: feedback, sensor fusion, learning algorithms and objective function-based control.

1. Feedback and modeling. An important aspect of adaptive control is feedback. The robot must continuously receive information about its current state and the state of the environment. This data is used to correct and optimize the robot's actions. Sensors play a key role in providing feedback, their data allows the robot to receive information about position, movement, force, temperature and other characteristics of the environment. In addition, modeling of the system is important in adaptive control. The robot must have an understanding of the dynamics of the environment and its own dynamics to predict future states. A system model allows you to predict how the robot will behave in different conditions and what control actions will lead to the desired result.

2. Sensor Fusion. Many sensors on a robot provide a variety of data about the state of the environment. However, this data can be noisy, incomplete, or even contradictory. Sensor fusion is a technique that combines data from different sensors to obtain more accurate and complete information about the environment. This allows the robot to have a more reliable picture of the current state of the world and make more informed decisions.

3. Learning and Adaptation Algorithms. The basis of adaptive control is learning and adaptation algorithms. Robots must be able to extract knowledge from experience and use this information to improve their behavior. Reinforcement learning, neural network methods, and genetic algorithms are some of the techniques used in adaptive control to self-learn robots. Learning algorithms allow robots to adapt to new conditions, explore unknown environments, and optimize their behavior to achieve their goals.

4. Objective Function Control. Adaptive control is often based on the use of objective functions or criteria. The objective function defines what the robot should achieve and is a measure of the quality of its actions. The robot strives to maximize or minimize this function, depending on the tasks at hand. Objective function control allows the robot to make decisions that best meet the requirements and conditions of the environment. Adaptive control is an important step in the development of robotics and expands the capabilities of robots in many application areas. Using the principles of feedback, sensor fusion, learning algorithms, and objective function control, robots are able to cope with variable and uncertain conditions, demonstrating outstanding flexibility and efficiency in task performance.

Here we will limit ourselves to considering examples of control systems for manipulation robots with the most developed video sensor devices based on applied television units (ATU), photodiode matrices and solid-state optical-electronic devices with charge coupling (CCD).

There are several directions in the creation of machine vision systems (MVS) for manipulation robots. For mass production, specialized MVS are usually developed, an example of which can be a system for a precision welding robot.

Control system for a precision welding robot. The main technological process for assembling microelectronic devices (MD) is internal wire assembly using microwelding. Microwelding of contact pads of MD crystals with dimensions from 40 X 40 to 500 X 500 µm is carried out with a wire with a diameter of 20-500 µm. The complexity of the internal switching circuit between crystals, numbering up to several thousand connections in one device, and the need to combine precision elements under a microscope with high accuracy determine the feasibility of robotizing this technological process. One of the main tasks of the robot control system is to control the precision stepper electric drive in accordance with the reference program for positioning the microtool performing welding.

A simplified structural diagram of the adaptive robot is shown in Fig. 1.1. Illumination of the original object (a set of crystals of a given microchip) is performed by infrared and visible light through an optical system. The light flux reflected from the object, through the optical system and the IR filter, enters the light-sensitive field of the CCD. The signals from the control unit ensure normal functioning of the CCD. At the output, the light information is presented as a sequence of electrical signals, which after conversion are sent to the computer. The purpose of processing visual information is to determine the coordinates of the centers of gravity (centers of form) of the crystal contact pads, taken as reference marks. The true coordinates of the position of the crystals of the microprocessor relative to the coordinate axes are calculated from these marks. The determination of corrections for each of the coordinates is made based on a comparison of the coordinates of the presented object with the reference one. These corrections accordingly adjust the positioning program that controls the movement of the coordinate table.

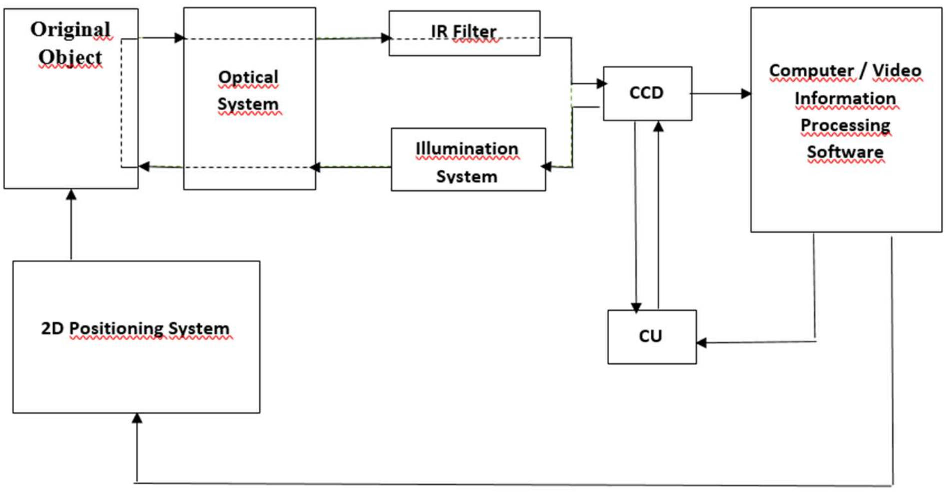

Fig. 1.1. Simplified structural diagram of an adaptive robot

For serial and especially small-scale production, it is advisable to create a VS with mathematical support that allows for simple restructuring when changing the sets of objects to be recognized. In addition, such VS, as a rule, should be suitable for working with manipulators of various types. An example of such VS is the system developed at the Institute of Cybernetics of the Academy of Sciences of the Ukrainian SSR, designed to work with binary images of objects. It is designed to work with binary (two-gradation) images obtained using television cameras on vacuum devices or on CCD matrices. A feature of the mathematical support of the VS is the ability to use not one, but several different image recognition algorithms. The system provides for a training stage, which is carried out by presenting the system with an object while simultaneously indicating the class name of this object.

Adaptive control systems are applied across various domains of robotics. Below is a summary of how they are used in specific fields:

Domain	Role of Adaptive Control
Industrial Robotics	Enables task-specific motion planning, tool path adjustment, and correction of dynamic inaccuracies.
Autonomous Vehicles	Facilitates real-time path planning, detection and prediction of environmental elements, and behavioral adaptation.
Medical Robots	Provides precise and adaptive control for soft-tissue manipulation, prosthetics, and surgical interventions.
Agriculture	Assists with terrain navigation, obstacle avoidance, and adaptation to changing weather or crop conditions.
Disaster Response	Supports autonomous navigation in unknown, cluttered, and hazardous environments with limited visibility or structural instability.

A bar chart was created to compare the application impact of each key adaptive control technology. This impact assessment is based on:

Frequency of appearance in recent academic literature

Prevalence in industrial and commercial robotic applications

The chart demonstrates that deep neural networks and reinforcement learning currently have the highest impact, followed closely by sensor fusion and model predictive control, while classical adaptive systems maintain moderate relevance in modern applications.

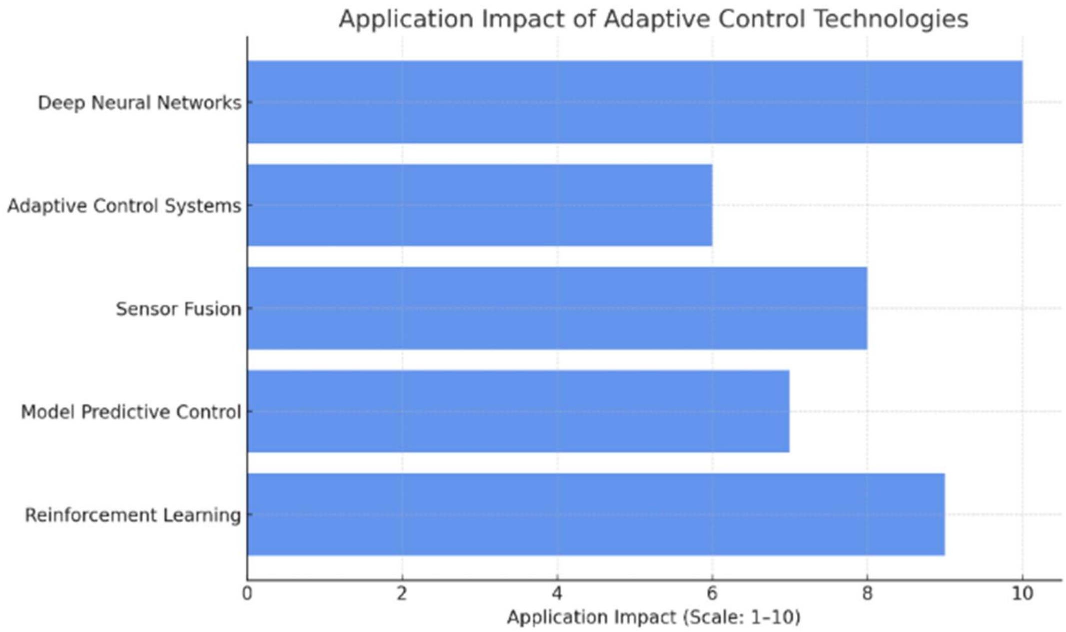

Fig. 1.2. The impact of key adaptive control technologies in robotics.

Discussion

Adaptive robot control systems are moving toward hybrid architectures, which combine classical control theory with machine learning and probabilistic reasoning. For instance, reinforcement learning is increasingly embedded into model predictive controllers, enabling long-term planning with real-time flexibility.

However, real-world implementation faces several challenges:

Lack of generalization in learned models

Computational limits for onboard learning

Safety and explainability in human–robot collaboration

Legal and ethical concerns regarding autonomous behavior

Emerging research focuses on meta-learning, lifelong learning, and zero-shot adaptation to further enhance robot adaptability.

Conclusion

The evolution of robotics is inseparably linked with the development of adaptive control methods. By integrating AI-driven learning, real-time data processing, and predictive modeling, robots are becoming capable of operating in environments that previously required human-level reasoning. Future systems will need to balance autonomy with safety, transparency, and trustworthiness—demands that will shape both research and engineering priorities.

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