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MANIPULATOR CONTROL SYSTEMS REVIEW

Abstract. This review focuses on manipulator control systems, which are systems that control the movement of manipulators, a type of robot programmed to move in specific ways. The control systems send commands to actuators (such as motors or pneumatic cylinders) based on input from sensors (such as position or force sensors) to control the movement of the manipulator's joints. Manipulator control systems have a wide range of applications in industries such as robotics, industrial automation, and medical and surgical robotics.

The review covers the different types of manipulator control systems, including open-loop, closed-loop, and hybrid control systems, and their applications. It also discusses control strategies, including Proportional-Integral-Derivative (PID) control, Linear Quadratic Regulator (LQR) control, and Model Predictive Control (MPC). The review also covers sensors and actuators used in manipulator control systems and the challenges and future directions in the field.

The review provides a comprehensive understanding of the current state of manipulator control systems and highlights the recent developments and future directions in the field, providing insights for future research and development.

Keywords. Control system, Manipulator, Robotics, Control strategies, Control Systems Design.

Introduction.

A manipulator control system is a system that controls the movement of a manipulator, which is a type of robot that can be programmed to move in a specific way. The control system is responsible for sending commands to the actuators (such as motors or pneumatic cylinders) that move the manipulator's joints, based on input from sensors (such as position or force sensors), as illustrated in fig. 1.

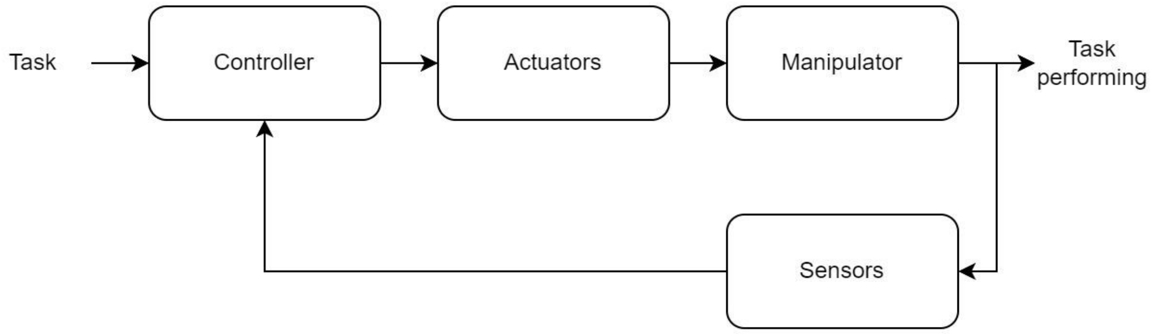

Figure 1 – General structure of manipulator system

The importance of manipulator control systems in various industries cannot be overstated. They have a wide range of applications in fields such as robotics, industrial automation, and medical and surgical robotics. In the robotics industry, manipulator control systems are used to control the movement of robotic arms in manufacturing and assembly operations. In industrial automation, they are used to control the movement of machines and equipment in processes such as welding [1], painting [2], and material handling [3]. In the medical field, manipulator control systems are used to control the movement of surgical robots [4], which can perform precise and delicate procedures with minimal invasiveness. This review will cover the different types of manipulator control systems, control strategies, sensors and actuators, applications, challenges, and future directions. We will also discuss the recent developments and future directions in manipulator control systems research, and the implications for future research and development. This will provide a comprehensive understanding of the current state of manipulator control systems and the direction in which the field is heading.

Materials and methods.

Types of Manipulator Control Systems.

Control strategies in manipulator control systems refer to the methods and techniques used to control the movement and behavior of a manipulator robot. They play a crucial role in determining the accuracy and efficiency of the manipulator's performance. There are three main types of manipulator control systems: open-loop [5], closed-loop [6], and hybrid [7] control systems. Open-loop systems do not use feedback from sensors to adjust control commands, while closed-loop systems do. Hybrid systems use a combination of both.

Open-loop control systems (fig. 2), also known as non-feedback control systems, do not use any feedback from sensors to adjust the control commands sent to the actuators. Instead, they rely on pre-determined or pre-programmed control commands to move the manipulator. These systems are simple and easy to implement but are not very robust to changes in the system's dynamics or external disturbances. They are typically used in simple applications where the system's dynamics are well-known and the environment is highly controlled.

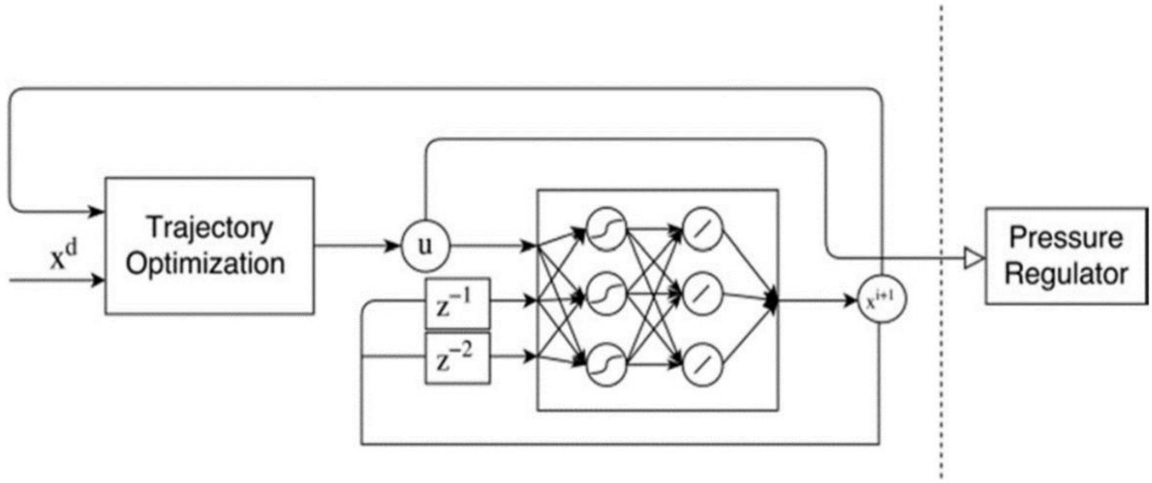

Figure 2 – Structure of open-loop controller of soft robotic manipulator [5]

Closed-loop control systems (fig. 3), also known as feedback control systems, use feedback from sensors to adjust the control commands sent to the actuators. The control system compares the actual position or other state of the system to the desired position or state and uses the difference (error) to adjust the control commands. This allows the system to respond to changes in the system's dynamics or external disturbances, making it more robust and accurate. However, closed-loop control systems are more complex than open-loop systems and are used in applications where the system's dynamics are not well-known or the environment is not highly controlled.

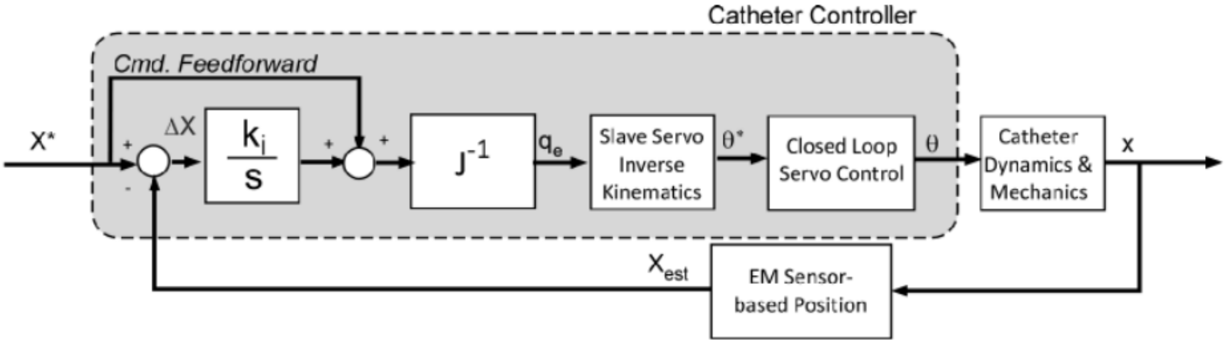

Figure 3 – Structure of closed-loop controller of continuum manipulator [6]

Hybrid control systems (fig. 4) combine elements of both open-loop and closed-loop control systems. They use a combination of pre-determined or pre-programmed control commands and feedback from sensors to control the manipulator. Hybrid control systems are used in applications where the system's dynamics and the environment are not well-known and where a combination of feedforward and feedback control is required.

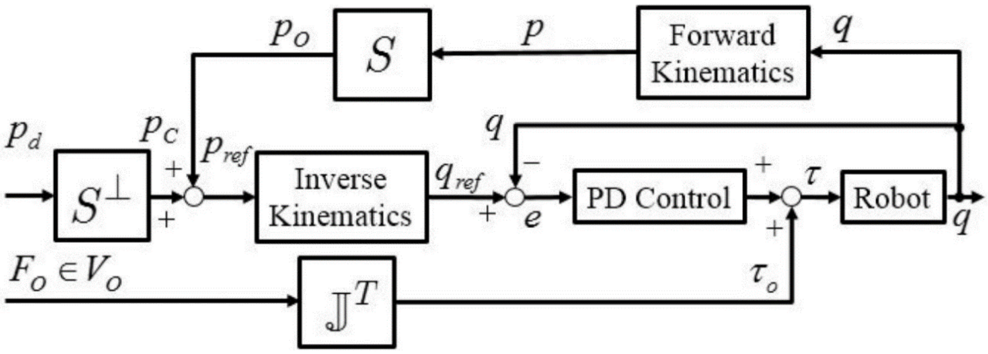

Figure 4 – Structure of hybrid open-loop / closed-loop controller of human-robot [7]

In summary, open-loop control systems are simple and easy to implement but not robust to changes, closed-loop control systems are more robust and accurate but complex, and hybrid control systems are a combination of both and are used in applications where the system's dynamics and the environment are not well-known.

Control Strategies.

Common control strategies include Proportional-Integral-Derivative (PID) [8], Linear Quadratic Regulator (LQR) [9], and Model Predictive Control (MPC) [10]. PID is the most widely used and it uses the error between the desired position or state and the actual position or state to adjust the control commands. LQR is a powerful strategy for complex systems with multiple inputs and outputs, but it requires a good model of the system. MPC is a powerful strategy for systems with constraints and disturbances, but it also requires a good model of the system.

Proportional-Integral-Derivative (PID) control (fig. 5) is the most widely used control strategy for manipulator control systems. It is a feedback control strategy that uses the error between the desired position or state and the actual position or state to adjust the control commands. The controller is composed of three components: the proportional, integral, and derivative controllers. The proportional controller is responsible for reducing the error by a proportion of the error, the integral controller is responsible for eliminating the residual error, and the derivative controller is responsible for reducing the rate of change of the error.

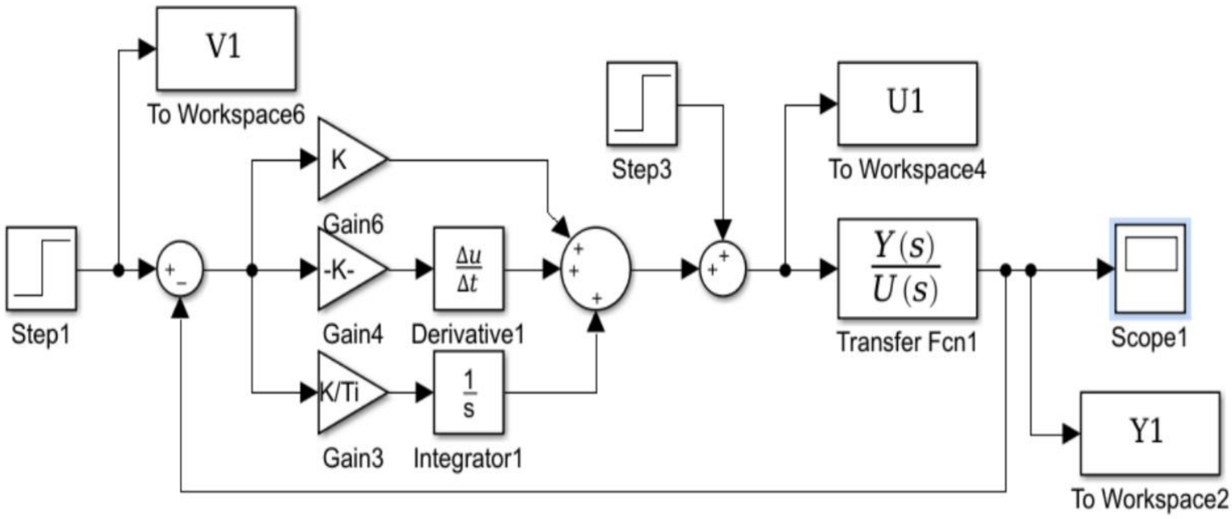

Figure 5 – PID controller structure [11]

Linear Quadratic Regulator (LQR) control (fig. 6) is a feedback control strategy that uses a mathematical optimization algorithm to determine the control commands that minimize a cost function. The cost function is a mathematical representation of the system's performance and can include factors such as the error, the rate of change of the error, and the control effort. LQR control is a powerful control strategy that can handle complex systems with multiple inputs and outputs, but it can be computationally intensive and requires a good model of the system.

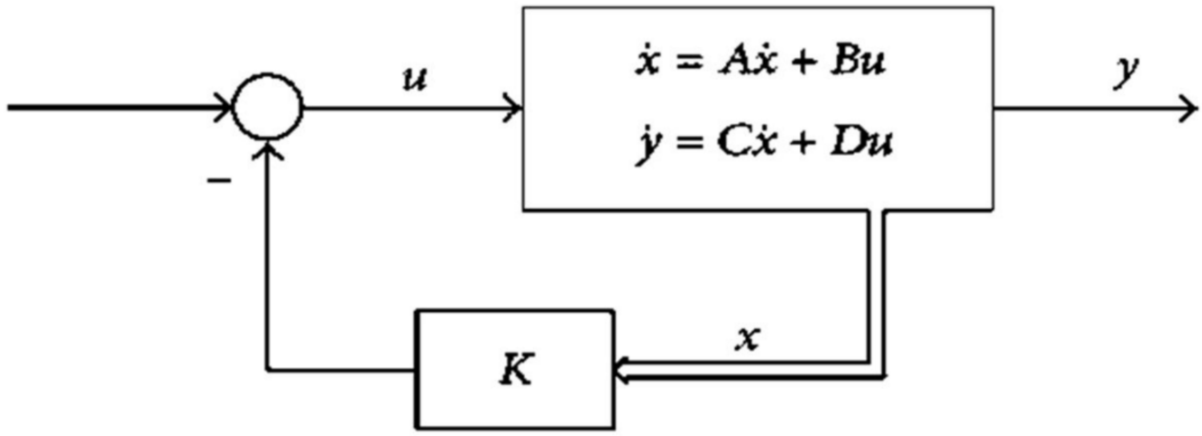

Figure 6 – Architecture of LQR control system [9]

Model Predictive Control (MPC) (fig. 7) is a control strategy that uses a mathematical model of the system to predict future behavior and determine the control commands that will achieve the desired performance. The control system uses the predicted behavior to plan a sequence of control commands that will optimize the system's performance over a finite horizon of time. MPC is a powerful control strategy that can handle complex systems with constraints and disturbances, but it requires a good model of the system and can be computationally intensive.

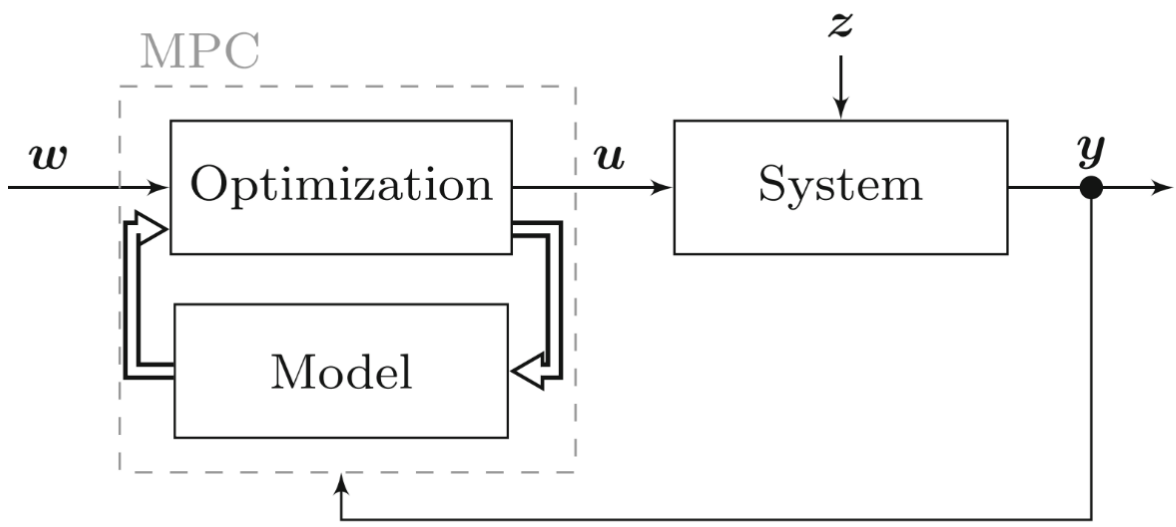

Figure 7 – Simplified block diagram of a MPC-based control loop [10]

In summary, PID control is the most widely used control strategy, it uses the error between the desired position or state and the actual position or state to adjust the control commands. LQR control is a powerful control strategy that can handle complex systems with multiple inputs and outputs, but it can be computationally intensive. MPC is a powerful control strategy that can handle complex systems with constraints and disturbances, but it requires a good model of the system and can be computationally intensive.

Sensors and Actuators.

Sensors are devices that measure various physical quantities such as position, velocity, and force. They are used in manipulator control systems to provide feedback information to the control system. Some common sensors used in manipulator control systems include position sensors [12], velocity sensors [13], and force sensors [14].

Position sensors measure the position of the manipulator's joints or end-effector and can be based on various technologies, such as encoders, potentiometers, or laser interferometers.

Velocity sensors measure the velocity of the manipulator's joints or end-effector and can be based on technologies such as tachometers or optical encoders.

Force sensors measure the force exerted by the manipulator on the environment and can be based on technologies such as load cells, strain gauges, or piezoelectric sensors.

Actuators are devices that convert control commands into mechanical motion. They are used in manipulator control systems to control the motion of the manipulator. Some common actuators used in manipulator control systems include electric motors, pneumatic cylinders, and hydraulic cylinders.

Electric motors are widely used as actuators in manipulator control systems and can be controlled using techniques such as pulse width modulation (PWM) or direct torque control (DTC).

Pneumatic cylinders use compressed air to generate mechanical motion and are simple and robust, but not as precise as electric motors.

Hydraulic cylinders use pressurized fluid to generate mechanical motion and are powerful and precise, but also complex and expensive.

In summary, sensors provide feedback information to the control system by measuring physical quantities such as position, velocity and force, while actuators convert control commands into mechanical motion to control the motion of the manipulator. Electric motors, pneumatic cylinders, and hydraulic cylinders are common actuators used in manipulator control systems.

Applications.

Industrial automation. Manipulator control systems are widely used in industrial automation for tasks such as material handling, assembly, and welding. They are used in various industries such as automotive, aerospace, and electronics manufacturing to improve productivity and reduce human error.

Robotics. Manipulator control systems are also used in robotics for tasks such as grasping, manipulation, and navigation. They are used in various fields such as service robots, medical robots, and space robots to perform various tasks that are difficult or dangerous for humans to perform.

Nuclear power plants. Manipulator control systems are used in nuclear power plants for tasks such as fuel handling, maintenance, and decontamination. They are used to perform tasks that are difficult or dangerous for humans to perform, and they also help to minimize the exposure of workers to radiation.

Biomedical engineering. Manipulator control systems are used in biomedical engineering for tasks such as surgical robots, rehabilitation robots, and prosthetics. They are used to perform tasks that are difficult or dangerous for humans to perform, and they also help to improve the quality of life for patients.

Military and defense. Manipulator control systems are used in military and defense for tasks such as bomb disposal, mine clearance, and reconnaissance. They are used to perform tasks that are difficult or dangerous for humans to perform, and they also help to minimize the risk to human soldiers.

In summary, Manipulator control systems are widely used in various fields such as industrial automation, robotics, nuclear power plants, biomedical engineering, military and defense to perform various tasks that are difficult or dangerous for humans to perform, improve productivity and reduce human error, and minimize the risk to human lives.

Results and Discussion.

One of the main challenges in manipulator control systems is achieving real-time control. The control system needs to process sensor data, compute control commands, and actuate the manipulator in a timely manner. This is especially challenging for high-speed or high-precision tasks.

Singularity is a condition where the manipulator's degrees of freedom become linearly dependent, and the inverse kinematics solution becomes ill-defined. Singularity avoidance is a major challenge in manipulator control systems, and various strategies have been proposed to address this issue.

Another challenge in manipulator control systems is achieving adaptive control. The manipulator's dynamics can change due to variations in the environment, payload, or wear and tear. Adaptive control strategies are needed to ensure stable and efficient operation under these conditions.

As manipulator control systems are increasingly used in fields such as service robots, medical robots, and prosthetics, the interaction between humans and robots becomes an important aspect of the control system. Human-robot interaction (HRI) is an active research area, and various strategies have been proposed to improve the safety, usability, and acceptability of manipulator systems.

In recent years, the use of Machine Learning and Artificial Intelligence techniques have gained attention in the field of manipulator control systems. These techniques can help to improve the performance, adaptability, and autonomy of the control systems.

Future research in the field of manipulator control systems is likely to focus on addressing these challenges and incorporating advanced technologies such as Machine Learning, Artificial Intelligence and Network communication to improve the performance, adaptability, and autonomy of the control systems.

In summary, the main challenges in manipulator control systems are achieving real-time control, singularity avoidance, adaptive control, human-robot interaction and incorporating advanced technologies such as Machine Learning and Artificial Intelligence. Future research in the field of manipulator control systems is likely to focus on addressing these challenges and incorporating advanced technologies to improve the performance, adaptability, and autonomy of the control systems.

Conclusion.

Manipulator control systems are critical components in various industries and fields, such as industrial automation, robotics, nuclear power plants, biomedical engineering, and military and defense. They are used to perform tasks that are difficult or dangerous for humans to perform, improve productivity and reduce human error, and minimize the risk to human lives.

This review has discussed the different types of manipulator control systems, control strategies, sensors and actuators, applications, and challenges and future directions. It has highlighted the importance of real-time control, singularity avoidance, adaptive control, human-robot interaction, and incorporating advanced technologies such as Machine Learning and Artificial Intelligence in manipulator control systems.

In conclusion, manipulator control systems are a complex and rapidly evolving field, and continued research and development is needed to address the challenges and incorporate advanced technologies to improve the performance, adaptability, and autonomy of the control systems.

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МАНИПУЛЯТОРДЫ БАСҚАРУ ЖҮЙЕЛЕРІН ШОЛУ

Аңдатпа. Бұл шолу манипуляторларды басқару жүйелеріне, яғни белгілі бір қозғалыстарға бағдарламаланған роботтар сияқты манипуляторлардың қозғалысын басқаратын жүйелерге бағытталған. Басқару жүйелері қол буындарының қозғалысын басқару үшін сенсорлардан (позиция немесе күш сенсорлары сияқты) кіріс негізінде жетектерге (мысалы, қозғалтқыштар немесе пневматикалық цилиндрлер) командалар жібереді. Манипуляторларды басқару жүйелері робототехника, өнеркәсіптік автоматтандыру, медициналық және хирургиялық робототехника сияқты салаларда кең ауқымды қолданбаларға ие.

Шолу манипуляторларды басқару жүйелерінің әртүрлі түрлерін, соның ішінде ашық циклді, жабық циклді және гибридті басқару жүйелерін, сондай-ақ олардың қолданбаларын қамтиды. Ол сондай-ақ бақылау стратегияларын, соның ішінде пропорционалды-интегралдық-туынды (PID) басқаруды, сызықтық квадраттық бақылауды (LQR) және модельдік болжамды басқаруды (MPC) талқылайды. Шолу сонымен қатар манипуляторларды басқару жүйелерінде қолданылатын сенсорлар мен жетектерді, сондай-ақ осы саладағы қиындықтар мен болашақ бағыттарын қамтиды.

Шолу манипуляторларды басқару жүйелерінің ағымдағы жай-күйінің жан-жақты көрінісін береді және болашақ зерттеулер мен әзірлемелер үшін ақпарат бере отырып, осы саладағы соңғы әзірлемелер мен болашақ бағыттарын көрсетеді.

Түйінді сөздер. Басқару жүйесі, манипулятор, робототехника, басқару стратегиялары, басқару жүйелерін жобалау.

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ОБЗОР СИСТЕМ УПРАВЛЕНИЯ МАНИПУЛЯТОРОМ

Аннотация. В этом обзоре основное внимание уделяется системам управления манипуляторами, то есть системам, управляющим движением манипуляторов, типа роботов, запрограммированных на определенные движения. Системы управления отправляют команды исполнительным механизмам (таким как двигатели или пневматические цилиндры) на основе входных данных от датчиков (таких как датчики положения или силы) для управления движением суставов манипулятора. Системы управления манипуляторами имеют широкий спектр применения в таких отраслях, как робототехника, промышленная автоматизация, медицинская и хирургическая робототехника.

Обзор охватывает различные типы систем управления манипуляторами, включая разомкнутые, замкнутые и гибридные системы управления, а также их приложения. В нем также обсуждаются стратегии управления, в том числе пропорционально-интегрально-дифференциальное (ПИД) управление, управление с помощью линейно-квадратичного регулятора (LQR) и управление с прогнозированием моделей (MPC). Обзор также охватывает датчики и приводы, используемые в системах управления манипуляторами, а также проблемы и будущие направления в этой области.

Обзор дает всестороннее представление о текущем состоянии систем управления манипуляторами и освещает последние разработки и будущие направления в этой области, предоставляя информацию для будущих исследований и разработок.

Ключевые слова. Система управления, манипулятор, робототехника, стратегии управления, проектирование систем управления.

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