Optimization of Energy Consumption in Industrial Robots, A Review

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Optimization of energy consumption in industrial robots, a review

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ABSTRACT

Optimization of energy consumption in industrial robots can reduce operating costs, improve performance and increase the lifespan of the robot during part manufacturing. Choosing energy-efficient components such as motors, drives, and controllers can significantly reduce energy consumption in industrial robots. Over-sized motors and heavy robot arms can waste energy and decrease efficiency of industrial robots. By optimizing the robot programs and reducing idle time in robot operations, the amount of spent time can be reduced to minimize energy consumption of industrial robots. By using energy-efficient motors and drives, the amount of energy consumed by the robot can be reduced. Also, regular maintenance can reduce energy consumption of industrial robots by providing maximum efficiency for the robot's components. By implementing energy management systems, energy consumption of industrial robot can be monitored and analyzed to optimize energy consumption of industrial robot during working conditions. To minimize lost energy and reuse the energy usage during working times, regenerative braking can be used in the robots. The process of part manufacturing can be optimized in order to minimize the robot's movements and energy usage during working times of industrial robots. To analyze and optimize energy consumption in working schedules of industrial robots, different methodologies from recent published papers are reviewed in the study. Proper robot selection, energy-efficient robot motor and low wight robot arms, efficient programming of working schedules, regenerative braking system, regular maintenance of robot elements and optimized process of part production regarding the minimization of energy usage are discussed to optimize the energy consumption in industrial robots. As a result, future research works in the research field can be presented in order to optimize energy consumption, reduce operational costs, and increase sustainability of industrial robot operations in terms of productivity enhancement of part manufacturing.

1. Introduction

Industrial robots are increasingly utilized in manufacturing and industrial applications due to their ability to perform repetitive tasks with high accuracy and speed. However, one of the key concerns with the use of industrial robots is energy consumption during working times. Industrial robots consume energy during their operation, typically in the form of electrical power for the different motors and controlling units. The amount of energy consumed by an industrial robot depends on various factors, such as the type of robot, size, the tasks it performs, and operational conditions [1]. Due to high-volume of industrial robots applications in different industries, the optimization of energy consumption of industrial robots can significantly impact on the efficiency of part

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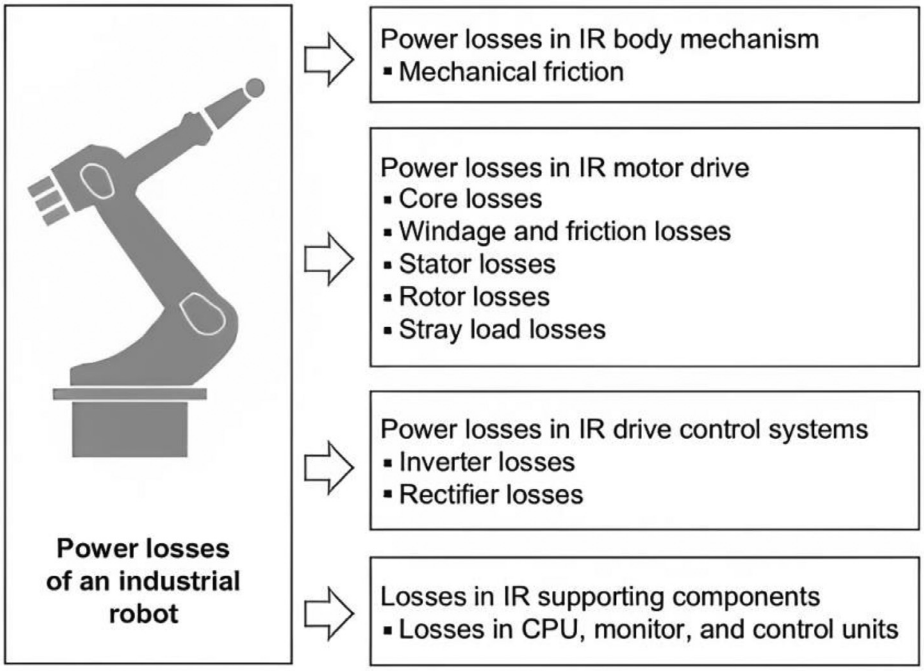

Fig. 1. Power losses in industrial robots [8].

manufacturing [2]. So, advanced industrial robots are designed to be energy-efficient during working schedules in order to enhance productivity in part manufacturing. Advanced features such as regenerative braking and low-power modes that help to reduce energy consumption during working times of industrial robots are designed in order to minimize energy consumption in working conditions of industrial robots [3]. The amount of energy consumption can vary depending on several factors, such as the type of robot, the task it is performing, the operating conditions, and the efficiency of its components [4,5].

Some of the main factors that can affect the energy consumption of industrial robots include:

1. Type of robot: Different types of robots have different energy requirements. For example, a large, heavy-duty robot may require more energy to operate than a small, lightweight robot.
2. Task performance: The energy consumption of a robot will also depend on the type of task it is performing. Tasks that require a lot of movement or heavy lifting may require more energy than tasks that are more static [6].
3. Operating conditions: The energy consumption of a robot can also be affected by the operating conditions, such as temperature, humidity, and the presence of dust or other contaminants [7].

Power losses in industrial robots are shown in the Fig. 1 [8].

Optimizing the energy consumption of industrial robots is important not only for reducing the cost of operation, but also for reducing the environmental impact of industrial processes [9,10]. Energy consumption optimization in industrial robots is an essential aspect of green manufacturing, as it helps reduce the carbon footprint and operating costs of the manufacturing process [11]. By implementing energy-saving measures, manufacturers can reduce their environmental impact while also improving productivity in part manufacturing process [12,13]. To minimize energy consumption in industrial robots, industry managers can take several steps, such as optimizing the design of the robot to reduce weight and improve energy efficiency, using more efficient motors and controllers, implementing energy-saving software algorithms, and reducing idle time when the robot is not in use [14]. Additionally, the energy consumption of their robots can be monitored in order to implement energy management strategies and improve efficiency of part production [15]. The process requires a holistic approach that considers the robot's design and operation, as well as the manufacturing process optimization in order to minimize the energy consumption in process of part production [16].

To optimize the energy consumption of industrial robots, application of data-driven methodology is studied [17]. U-shaped robotic assembly is designed and optimized in order to minimize the energy consumption during assembly process [18]. Intelligent path optimization is proposed in order to minimize the energy consumption in welding robots [19]. In order to analyze and minimize the low-carbon emission and noise in U-shaped robotic assembly line, gray wolf optimization methodology is developed [20]. Fault detection and diagnosis of industrial robot based on power consumption modeling is presented in order to minimize the potential failures in the robot joints that affect the power rate patterns in robot working times [21]. To minimize redundant weight and energy consumption in industrial robots, optimized robot arm designing procedure is presented [22]. Optimal robot speed decisions for material handling robot in a manufacturing cell is studied in order to minimize energy consumption in working conditions [23].

Optimization of the energy consumption of industrial robots is investigated in order to provide optimized energy consumption of industrial robots in working conditions [24]. Automated robotic polishing system is studied in order to provide processing energy modeling and optimization during working conditions [25]. To minimize energy consumption in industrial robots, trajectory planning and optimization for a par4 parallel robot based on energy consumption is proposed [26]. Multi-objective optimization for energy-efficient flexible job shop scheduling problem with transportation constraints is proposed in order to minimize energy consumption in industrial robots [27].

Soori et al. suggested virtual machining techniques to evaluate and enhance CNC machining in virtual environments [28–31]. To investigate and enhance performance in the component production process employing welding procedures, Soori et al. [32] suggested an overview of current developments in friction stir welding techniques. Soori and Asamel [33] examined the implementation of virtual machining technology to minimize residual stress and displacement error throughout turbine blade five-axis milling procedures. Soori and Asmael [34] explored applications of virtualized machining techniques to assess and reduce the cutting temperature throughout milling operations of difficult-to-cut objects. Soori et al. [35] indicated an advanced virtual machining approach to improve surface characteristics throughout five-axis milling procedures for turbine blades. Soori and Asmael [36] created virtual milling processes to reduce displacement error throughout five-axis milling operations of impeller blades. In order to analyze and develop the process of part production in virtual environments, virtual product development is presented by Soori [37]. Soori and Asmael [38] proposed an overview of current advancements from published research to review and enhance the parameter technique for machining process optimization. In order to improve the efficiency of energy consumption, the quality and availability of data across the supply chain, and the accuracy and dependability of component manufacture, Dastres et al. [39] proposed a review of RFID-based wireless manufacturing systems. Soori et al. [40] explored machine learning and artificial intelligence in CNC machine tools to boost productivity and improve profitability in production processes of component employing CNC machining operations. To improve the performance of machined components, Soori and Arezoo [41] reviewed the topic of measuring and reducing residual stress in machining operations. To improve surface integrity and decrease residual stress during Inconel 718 grinding operations, Soori and Arezoo [42] proposed the optimum machining parameters employing the Taguchi optimization method. In order to increase the life of cutting tools during machining operations, Soori and Arezoo [43] examined different method of tool wear prediction algorithms. Soori and Asmael [44] investigated computer assisted process planning to boost productivity in the part manufacturing procedure. Dastres and Soori [45] addressed improvements in web-based decision support systems to give solutions for data warehouse management using decision-making assistance. Dastres and Soori [46] reviewed applications of artificial neural networks in different sections, such as analysis systems of risk, drone navigation, evaluation of welding, and evaluation of computer simulation quality, to explore the execution of artificial neural networks for improving the effectiveness of products. Dastres and Soori [47] proposed employing communication system in environmental concerns to minimize the negative effects of technological advancement on natural catastrophes. To enhance network and data online security, Dastres and Soori [48] suggested the secure socket layer. Dastres and Soori [49] studied the developments in web-based decision support systems to develop the methodology of decision support systems by evaluating and suggesting the gaps between proposed approaches. To strengthen network security measures, Dastres and Soori [50] discussed an analysis of recent advancements in network threats. To increase the potential of image processing systems in several applications, Dastres and Soori [51] evaluated image processing and analysis systems. Dimensional, geometrical, tool deflection, and thermal defects have been modified by Soori and Arezoo [52] to improve accuracy in 5-axis CNC milling processes. Recent developments in published articles are examined by Soori et al. [53] in order to assess and improve the impacts of artificial intelligence, machine learning, and deep learning in advanced robotics. Soori and Arezoo [54] developed a virtual machining system application to examine whether cutting parameters affect tool life and cutting temperature during milling operations. Soori and Arezoo [55] studied the impact of coolant on the cutting temperature, roughness of the surface, and tool wear during turning operations with Ti6Al4V alloy. Recent developments from published papers are reviewed by Soori [56] in order to examine and alter composite materials and structures. Soori et al. [57] examined the Internet of things application for smart factories in industry 4.0 to increase quality control and optimize part manufacturing processes. To minimize cutting tool wear during drilling operations, Soori and Arezoo [58] designed a virtual machining system. Soori and Arezoo [59] decreased residual stress and surface roughness to improve the quality of items produced utilizing abrasive water jet machining. To enhance accuracy in turbine blades five-axis milling operations, deformation errors is calculated and compensated by Soori [60]. In order to analyze and enhance accuracy in CNC machining operations and structures, applications of finite element method in CNC machine tool modification are reviewed by Soori and Arezoo [61].

Recent achievements from published papers are reviewed in the study to analyze and optimize the energy consumption of industrial robots. In order to propose future research works in the interesting research field, the gaps between the published research works in the applications of different methodologies of energy consumption minimization in industrial robots are discussed. As a result, energy consumption optimization in industrial robots can lead to significant cost savings and reduce the environmental impact of manufacturing processes in terms of productivity and sustainability enhancement of part production.

2. Optimization of energy consumption in industrial robots

Optimizing energy consumption of industrial robots is an important consideration for manufacturers and industries which can lead to significant cost savings and reduce environmental impact [13]. Optimizing energy consumption in industrial robots can have significant benefits, such as reducing operational costs, increasing production efficiency, and improving environmental sustainability [62,63]. The first step in optimizing energy usage is to measure the energy consumption of the robot during operation. The process can be implemented by installing energy monitoring sensors and meters on the robot or its power source [64]. Experimental set up for

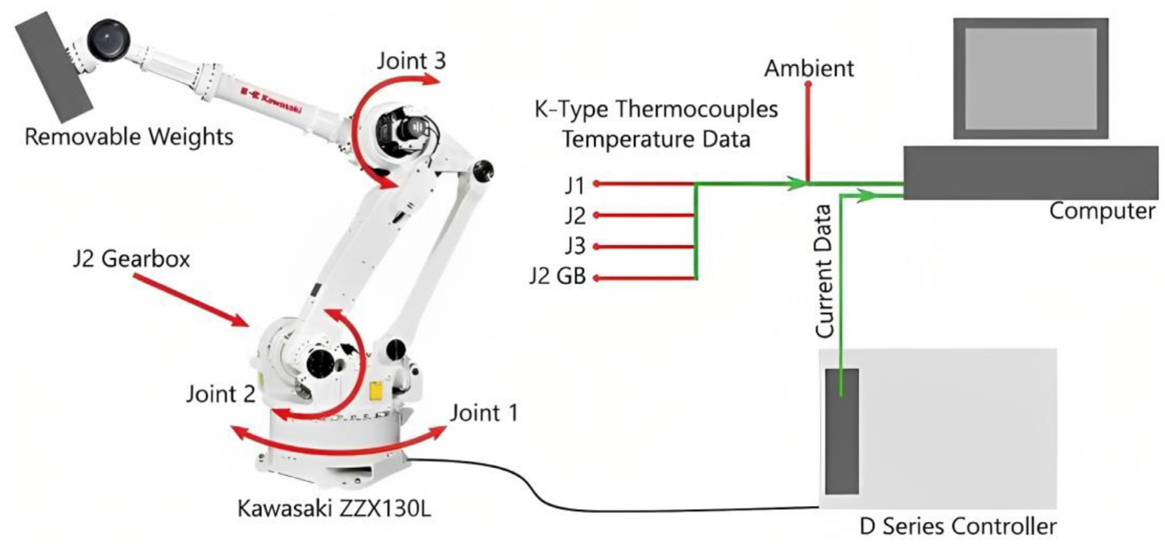

Fig. 2. Experimental set up for measuring temperatures (joints 1–3, joint 2 gearbox and ambient) and getting motor current data from IR controller [65].

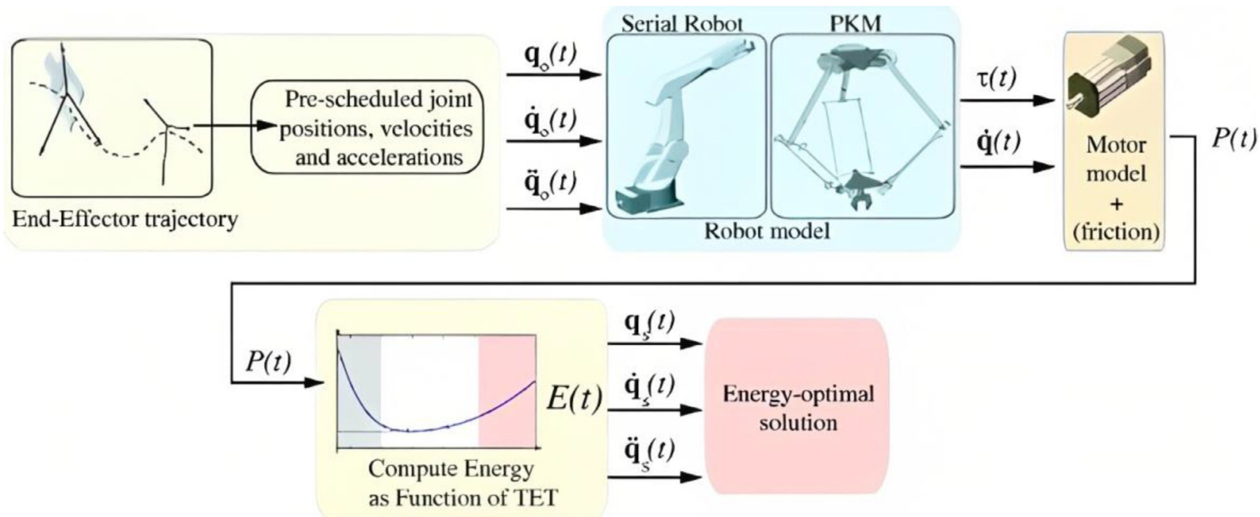

Fig. 3. Calculation of the energy consumption of industrial robots [1].

measuring temperatures (joints 1–3, joint 2 of gearbox and ambient) and getting motor current data from industrial robots controller are shown in the Fig. 2 [65]

After measuring the energy consumption, it is important to analyze the data to identify patterns and trends in energy usage. This analysis can be used in order to identify opportunities to optimize energy usage during working times of robots [66,67]. Calculation of the energy consumption of industrial robots in working conditions is shown in the Fig. 3 [1].

Existing methods for reducing the energy consumption of industrial robots is shown in the Fig. 4 [8].

Some strategies for energy consumption optimization of industrial robots are presented in this section. By implementing these steps, it is possible to monitor and optimize energy usage during the working period of robots, improving their efficiency, reducing costs, and increasing their lifespan.

2.1. Proper robot selection

Selecting the right industrial robot for the specific operation in manufacturing process is important in order to reduce energy consumption during working times. Robots which are bigger and heavier often need more energy to function than robots that are smaller and lighter. Using energy-efficient components, motors, batteries, and sensors can help to reduce energy consumption during

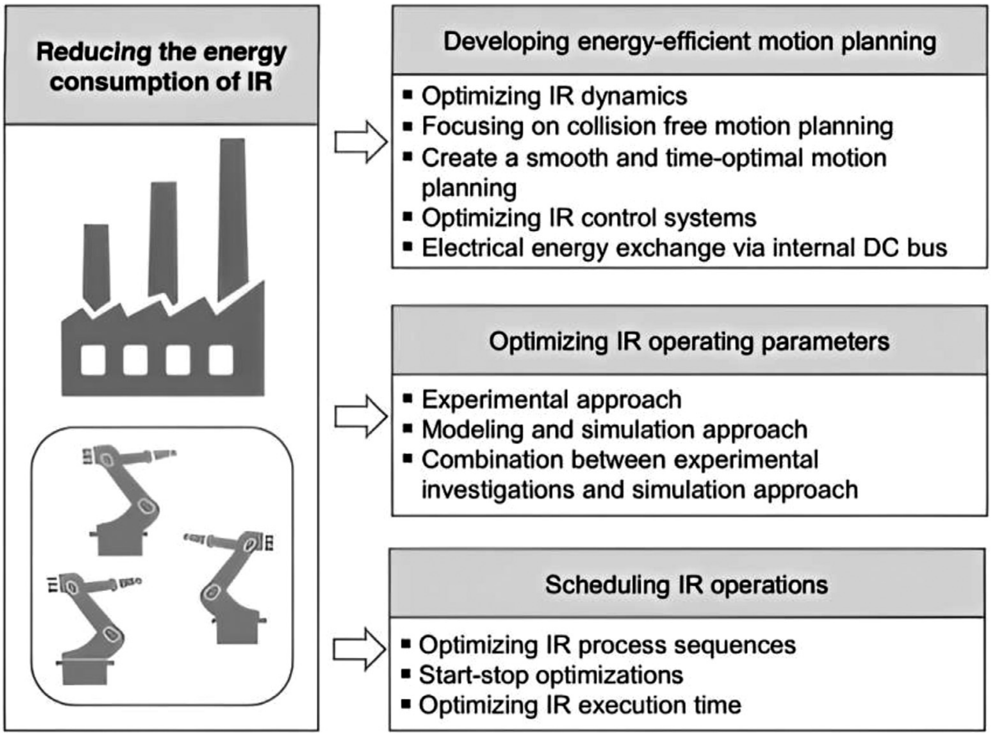

Fig. 4. Existing methods for reducing the energy consumption of industrial robots [8].

the working period of robots [68]. The right payload capacity, energy-efficient motors and drives should be selected regarding to the desired operations of industrial robots [69]. Here are some key factors to consider:

1. Payload capacity: A robot with a payload capacity that meets the demands of desired application should be selected. A robot with a higher payload capacity than necessary will consume more energy than needed, whereas a robot with a lower payload capacity may need to work harder to complete the task, leading to increased energy consumption [8].
2. Minimize robot weight: A robot's weight can have a significant impact on its energy consumption. By minimizing the weight of the robot and its payload, you can reduce the energy required to move it [70].
3. Robot arm reach area: It is important to choose a robot with an arm reach range that allows it to carry out the necessary activities without making unnecessary movements. A robot with a longer reach than necessary will consume more energy than required for the task [71,72].
4. Robot arm speed: A robot with arm speed that is appropriate for the application should be selected. A robot that moves too quickly may consume more energy than necessary, while a robot that moves too slowly may take longer to complete the task, resulting in increased energy consumption [73].
5. Energy efficiency features: A robot which is designed for energy efficiency features should be selected. Robots with features such as regenerative braking, energy recovery, and low-friction bearings can help reduce energy consumption [74].
6. Maintenance: well-maintained robots typically consume less energy. Regular maintenance and calibration of the robot's mechanical components, such as joints and bearings, can help minimize friction and energy losses. A robot that is easy to maintain, should be select in order to minimize time and cost of robot maintenance. Look for a robot with a user-friendly interface that allows for easy diagnosis and repair of potential issues [75].
7. Application-specific features: Consider robots with application-specific features such as vision systems, force sensing, and other advanced sensors. These features can help optimize the robot's energy consumption by allowing it to work more precisely and efficiently [76].
8. Flexibility: A robot that which can be reprogrammed and repurposed for different tasks should be selected, as this can reduce the need to purchase additional robots, thereby saving energy in the long run [77].
9. Minimize Inertia of moving arms: Inertia is the resistance of an object to changes in its motion. Minimizing the inertia of robot components, such as arms and joints, reduces the energy required to move them. This can be achieved by using lightweight materials or by optimizing the design of the robot components [78].

By considering these factors and selecting the proper robot for your application, energy consumption of industrial robots can be optimized in order to increase efficiency in process of part manufacturing.

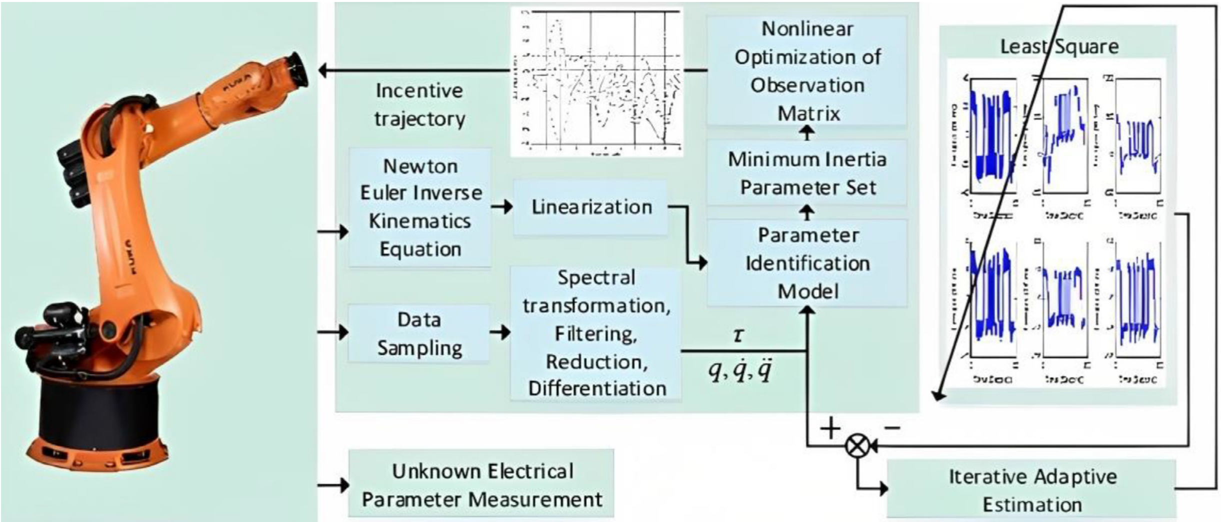

Fig. 5. The dynamic energy consumption model of the IRs based on parameter identification [84].

2.2. Energy-efficient motors in industrial robots

Industrial robots use electric motors to drive their various axes and perform tasks such as gripping, moving, and manipulating objects [79]. The amount of energy consumed by these motors depends on the robot's size, weight, and power requirements [80]. Larger, heavier robots generally require more energy to operate than smaller, lighter robots [81]. In addition to the motors, other components of industrial robots can also consume energy, such as sensors, control systems, and cooling systems [82]. Through the application of more effective designs and technologies in developing the robots components, the energy consumption of these components can be significantly decreased [83]. The type of robot's motor has a significant influence on the amounts of energy consumptions during working times of industrial robots. The quantity of energy utilized can be considerably decreased by selecting a motor which is suitable for the specific industrial operation and energy efficient. The dynamic energy consumption model of the IRs based on parameter identification is shown in the Fig. 5 [84].

Using energy-efficient motors is a crucial step towards optimizing energy consumption in industrial robots. Industrial robots often require a significant amount of energy to operate, and motors are one of the main components that consume energy [85]. Energy-efficient motors are designed to operate with high level of efficiency, which means they can convert more of the electrical energy they receive into mechanical energy [86]. Compared to conventional motors, energy-efficient motors can reduce energy consumption by up to 50% in working times of industrial robots. To incorporate energy-efficient motors into industrial robots, the following steps can be taken:

1. Identify the types of motors currently used in the robot and the energy consumption associated with each motor.
2. Research and identify energy-efficient motors that can replace the current motors in the robot.
3. Compare the energy consumption of the current motors to the energy-efficient motors to determine the potential energy savings [87].
4. Evaluate the performance of the energy-efficient motors and ensure they meet the required specifications and standards for the robot's operation.
5. Replace the current motors with energy-efficient motors and conduct performance testing to ensure that the robot operates as expected [88].

In addition to using energy-efficient motors, other measures can be taken to optimize energy consumption in industrial robots [89]. The optimization process of energy usage in motors of robots includes using regenerative braking systems, implementing power management strategies, and optimizing the robot's movements to minimize energy consumption. By implementing these measures, manufacturers can reduce energy consumption and achieve significant cost savings while also reducing their environmental impact [90].

2.3. Robot programming optimization

The way a robot's motions are programmed can have an influence on energy usage during operation. Optimizing the robot's path and motion of industrial robots to minimize unnecessary movement can reduce energy consumption in working schedules [91]. Minimize unnecessary movements, rapid acceleration, and deceleration, as these can consume significant energy. Smooth and efficient motion planning can reduce overall energy consumption. Optimizing robot path algorithms to generate energy-efficient paths can significantly reduce overall energy consumption. Techniques like trajectory optimization, path smoothing, and considering energy

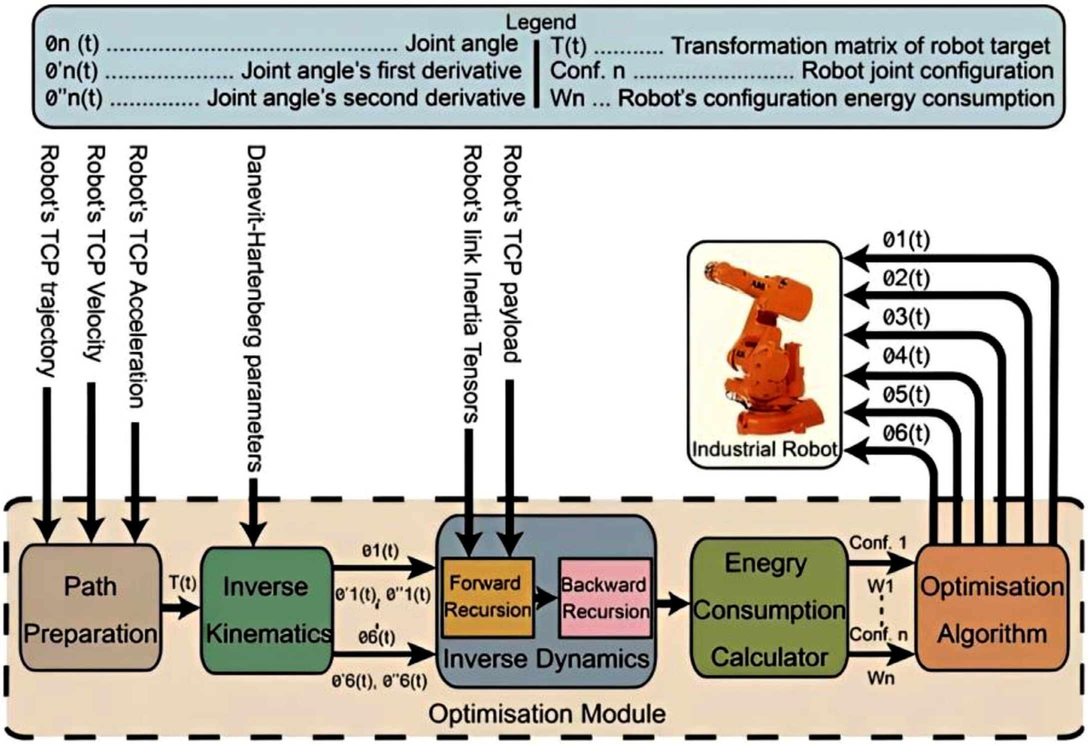

Fig. 6. Minimizing energy consumption for robot arm movement [71].

costs during path planning can be employed to minimize energy usage. [92]. Programming the robot to move at optimal speeds and minimizing excessive acceleration and deceleration can also help reduce energy consumption [93]. Simulation tools can be used in order to model and analyze the energy consumption of different robot behaviors, algorithms, and system configurations. This can help to identify energy-intensive areas and guide optimization efforts [94]. Machine learning and artificial intelligence techniques can be applied in order to learn energy-efficient behaviors and adapt the robot's actions based on the environment and task requirements. As a result, efficient working programming and smart working schedules of industrial robots can help to reduce the energy consumption of industrial robots by minimizing unnecessary movements and optimizing the robot's path [95]. This can be achieved by reducing unnecessary movements, optimizing the path taken by the robot, and optimizing the speed of the robot's movements [96]. Moreover, the optimized robot movement can also help to reduce wear and tear on the robot, resulting in lower maintenance costs. Minimizing energy consumption for robot arm movement is presented in Fig. 6 [71].

To minimize the energy consumption of robots during assembly in a cloud environment, energy-efficient robot is presented [64]. The Cloud-based energy-efficient approach for robotic application is shown in the Fig. 7 [64].

Intelligent path optimization is implemented in order to optimize energy consumption in welding robots [19]. As a result, the obtained results in energy consumption minimization for welding robots using intelligent path optimization is shown in the Fig. 8 [19].

Optimizing robot programming for energy consumption can be achieved through a variety of methods, including:

1. Minimizing unnecessary movements: One way to reduce energy consumption is to minimize the number of unnecessary movements performed by the robot [97]. This can be done by optimizing the robot's trajectory and reducing the number of times it changes direction or pauses during its movements. Additionally, reducing the overall distance travelled by the robot can also help save energy [98].
2. Optimize Trajectories: The robot's trajectory should be optimized to minimize energy consumption. This involves finding the most efficient path for the robot to move from one point to another while avoiding unnecessary movements [99]. Trajectory optimization can be achieved through programming or by using software tools [100].
3. Gripping Force Optimization: Adjusting the gripping force of the robot's end effector to the minimum necessary level can help save energy. Excessive gripping force requires more power to maintain, so using force sensors or other feedback mechanisms can ensure the optimal gripping force is applied while avoiding unnecessary energy expenditure.
4. Load and Torque Optimization: The robot's load and torque requirements can be optimized to match the task at hand. Oversized motors or excessive torque can lead to unnecessary energy consumption. Analyze the specific requirements of each task and select appropriate motor sizes and torque levels accordingly.

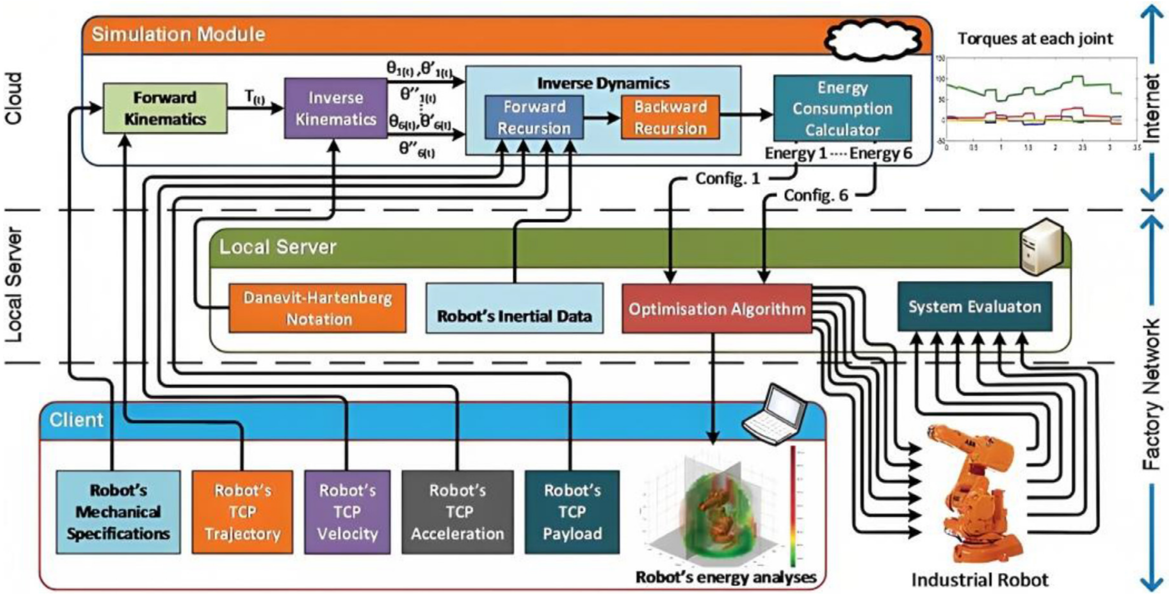

Fig. 7. Cloud-based energy-efficient approach for robotic application [64].

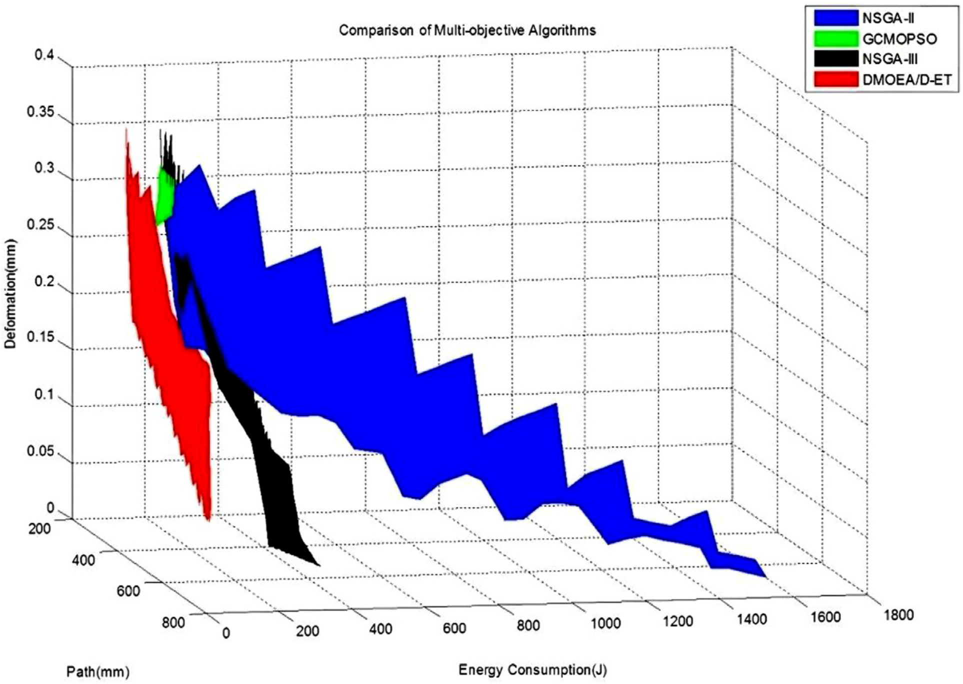

Fig. 8. Energy consumption minimization for welding robots using intelligent path optimization [19].

5. Utilizing energy-efficient components: Using energy-efficient components and motors in the robot's design can significantly reduce energy consumption. This can include using low-energy servo motors or optimizing the robot's pneumatic system to minimize energy waste.
6. Optimizing speed and acceleration: Controlling the robot's speed and acceleration can also help reduce energy consumption. By optimizing the robot's speed and acceleration profile, it can perform tasks more efficiently while using less energy [101].
7. Reducing idle time: Minimizing idle time can also help reduce energy consumption. This can be achieved by optimizing the robot's programming to minimize the time it spends waiting for instructions or parts [102].

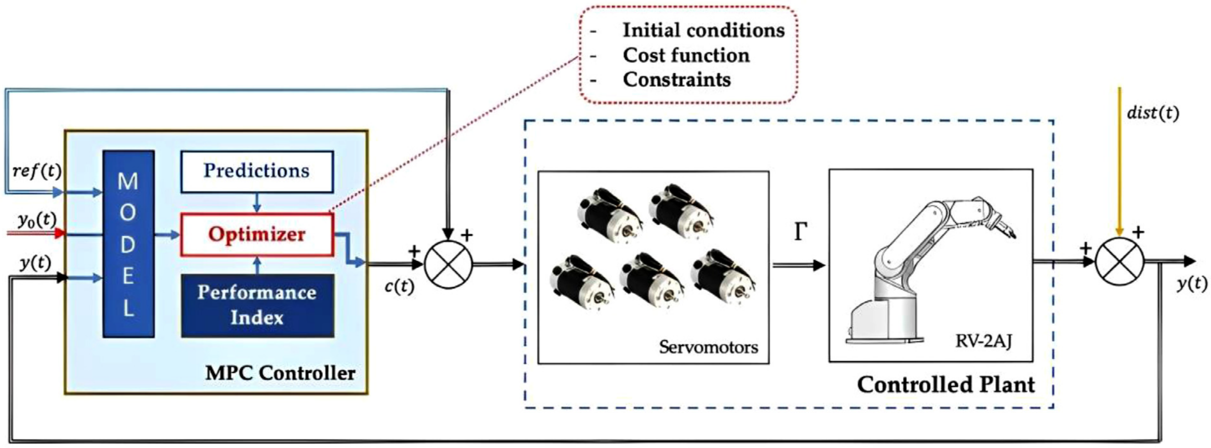

Fig. 9. The closed loop control of MPC in terms of energy consumption monitoring of industrial robots [101].

8. Idle and Standby Modes: Implement idle and standby modes for the robot when it is not actively performing tasks. During these periods, the robot can reduce power to non-essential components or even shut them down temporarily, conserving energy.
9. Using sensors and feedback systems: Using sensors and feedback systems can help the robot adapt to changing conditions and optimize its movements accordingly. For example, using force sensors can help the robot apply the right amount of force during a task, which can reduce energy waste [103].

Overall, optimizing robot programming for energy consumption requires a thorough understanding of the robot's design and operating environment. By implementing the methods above and continuously monitoring and adjusting the robot's programming, energy consumption can be significantly reduced, resulting in cost savings and a more sustainable operation.

2.4. Energy monitoring during working period of robots

Energy monitoring can play an important role in optimizing the energy consumption of industrial robots. Monitoring the robot's energy consumption can help identify areas where energy can be saved. This can help identify potential improvements in energy efficiency. The process can be implemented through energy monitoring software or hardware that tracks energy usage during working times of industrial robots [104]. The closed loop control of MPC in terms of energy consumption monitoring of industrial robots is shown in the Fig. 9 [101].

To optimize energy consumption, it is necessary to first understand how much energy is being used by the robot during various stages of operation [105]. By monitoring the energy usage of robots, it becomes possible to identify patterns of energy consumption, and to determine which processes and components are consuming the most energy of robots in order to be analyzed and optimized [106]. This can be done by installing energy meters at various points in the robot's system to measure the amount of energy being consumed. This data can then be analyzed to identify areas where energy use can be reduced [107]. Overall, energy monitoring is an important tool for optimizing energy consumption in industrial robots. By identifying areas where energy can be saved, and by implementing energy-efficient technologies and practices, it is possible to reduce energy costs and improve the sustainability of industrial operations.

2.5. Energy-saving features in controlling system of robots

Implementing energy-saving features can help to reduce energy consumption during the working period of robots. Advanced industrial robots are designed with energy-saving features, such as sleep mode or automatic shut-off during different working conditions [108]. This can include implementing sleep modes when the robot is idle, using regenerative braking to recover energy during deceleration, and using power management software to optimize energy usage [109]. These features can be programmed to activate when the robot is not in use, further reducing energy consumption. It can help reduce energy consumption in terms of energy minimization of industrial robots [110]. For example, some robots have sleep mode or power-saving mode that can be activated during periods of inactivity [111]. Here are some methods in which energy-saving features can be used to improve the efficiency of industrial robots:

1. Power management: Most industrial robots have a power management system that allows them to conserve energy when not in use. This system can be programmed to switch the robot to a low-power state when it is idle or not in use [112].
2. Efficient motors: The use of efficient motors can significantly reduce the energy consumption of industrial robots. High-efficiency motors have a lower power consumption and produce less heat, which can help to reduce the overall energy consumption of the robot [113].

3. Monitor battery health: The health of the robot's batteries can significantly impact on energy consumption during working times. Monitoring the battery's health can help to identify when it needs to be replaced in order to prevent unnecessary energy usage due to battery inefficiencies [114].
4. Energy-efficient sensors: Sensors are an integral part of industrial robots, and using energy-efficient sensors can significantly reduce their energy consumption. These sensors consume less power, produce less heat, and have a longer lifespan, making them a cost-effective option in the long run [115].
5. Intelligent control systems: Intelligent control systems can optimize the energy consumption of industrial robots by adjusting their speed and power consumption based on the task at hand. These systems can also monitor the robot's energy consumption in real-time and adjust its operations accordingly [116].

Overall, the application of energy-saving features in industrial robots can help to reduce their energy consumption, lower operating costs, and improve their environmental sustainability [117].

2.6. Regenerative braking system in industrial robots

Regenerative braking can be used to recover energy that is normally lost during braking time of industrial robots working schedules. This energy can be stored and reused to power the robot, reducing overall energy consumption. Some robots have regenerative braking, which allows them to recover energy during deceleration and reuse it to power the robot [118]. Regenerative braking is a technique used in many industrial robots to reduce energy consumption by recovering energy that would otherwise be lost during deceleration or stopping [119]. When the robot decelerates or stops, regenerative braking captures and stores the energy generated, which can be reused for subsequent movements, thereby reducing overall energy consumption. Here are the steps to implement regenerative braking in an industrial robot:

1. Identify the appropriate industrial robot: Select an industrial robot with the capability to implement regenerative braking. This may involve assessing the robot's mechanical and electrical systems to ensure they are capable of capturing and storing energy during braking [120].
2. Set up sensors: Install sensors on the robot to detect changes in speed and direction, as well as changes in load and torque. These sensors will help trigger the regenerative braking system during deceleration [121].
3. Design the regenerative braking system: Develop a system that can convert the kinetic energy generated during deceleration into electrical energy that can be stored and reused. This may involve designing an energy storage system such as a battery or capacitor bank to capture and store the energy [122].
4. Implement the regenerative braking system: Install the regenerative braking system on the robot and connect it to the robot's electrical and control systems. This may require modifying the existing control software to integrate the new system [123].
5. Test and optimize the system: Test the regenerative braking system to ensure it is working properly and efficiently. Fine-tune the system parameters to optimize energy recovery while minimizing any negative impacts on the robot's performance and safety [124,125].
6. Monitor and maintain the system: Regularly monitor the regenerative braking system to ensure it continues to function properly over time. Perform maintenance as needed to keep the system in good working order [126].

By implementing regenerative braking in an industrial robot, energy consumption can be significantly reduced in order to save costs over time.

2.7. Energy optimization for production processes

In addition to optimizing of the energy usage in robot, the overall production processes can also be optimized in order to reduce energy consumption in process of part production [127]. Manufacturers can optimize production processes for energy consumption in industrial robots, leading to reduced energy costs, lower carbon emissions, and improved sustainability. For example, robots can be programmed to operate in a way that minimizes unnecessary movements, which can help to reduce energy consumption [128]. They can also be equipped with sensors and other technologies that allow them to adjust their operation based on changes in the environment, such as variations in temperature or humidity [129]. This can include reducing the amount of waste produced or optimizing the flow of materials. A data-driven method for optimizing the energy consumption of industrial robots is shown in the Fig. 10 [17].

By implementing these strategies, it is possible to significantly reduce the energy consumption of industrial robots, leading to cost savings and a reduced environmental impact. A transfer-learning based energy consumption modeling method for industrial robots is shown in the Fig. 11 [130].

2.8. Regular maintenance of industrial robots

Regular maintenance can help to reduce energy consumption by ensuring that the robot's components are functioning optimally during working schedules of industrial robots. This includes checking and replacing worn or damaged components, as well as ensuring that the robot's lubrication is sufficient. Regular maintenance is crucial for ensuring energy efficiency and minimizing energy consumption in industrial robots [131]. Here are some tips for maintaining energy-efficient robots:

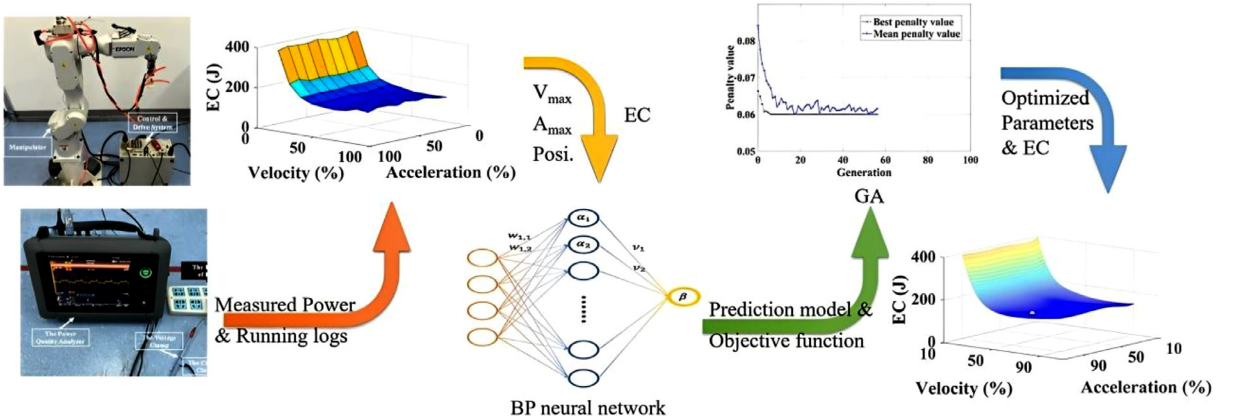

Fig. 10. A data-driven method for optimizing the energy consumption of industrial robots [17].

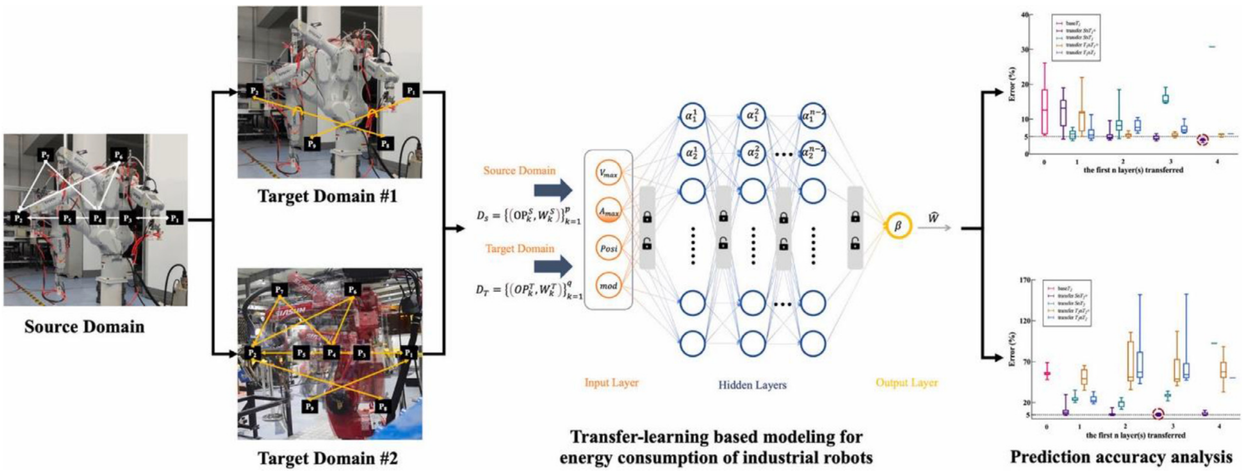

Fig. 11. A transfer-learning based energy consumption modeling method for industrial robot [130].

1. Implement predictive maintenance: Regularly check and maintain the robot's mechanical components such as gears, bearings, and belts. Poorly maintained mechanical components can increase the robot's energy consumption [132]. Regular maintenance can help prevent breakdowns and optimize energy usage in industrial machines and devices. Implementing predictive maintenance techniques, such as monitoring robot performance and detecting potential issues before they occur, can help ensure the robot is operating at peak efficiency [133].
2. Check and clean all air filters: Dirty air filters can reduce the efficiency of the robot's cooling system, which can lead to increased energy consumption. Regularly cleaning or replacing the air filters can help the robot cool more efficiently [134].
3. Keep the robot's electrical components, such as motors and sensors, clean and free of debris. Dirty or worn-out electrical components can cause the robot to consume more energy.
4. Lubricate the robot's moving parts, as friction can cause energy loss. Proper lubrication of robot joints can help reduce friction and improve the robot's movement efficiency. This can result in less energy consumption and increased longevity of the robot.
5. Monitor and optimize the robot's programming and control system to ensure that it is running at maximum efficiency. Implement algorithms and logic that minimize unnecessary computations, idle time, or redundant movements [135].
6. Train operators and maintenance personnel on energy-efficient practices. Raise awareness about the importance of energy optimization and encourage the adoption of best practices throughout the robot's lifecycle.
7. Replace worn-out or damaged components promptly to prevent energy loss.
8. Keep the robot's work area clean and unobstructed to ensure smooth operation, reducing energy consumption [136].
9. Conduct regular energy audits to identify areas where energy efficiency can be improved.

By implementing these maintenance tips, you can help ensure that your industrial robots operate efficiently and consume energy wisely.

3. Conclusion and future research work directions

Optimization of energy consumption in industrial robots is an important research area, as it can lead to significant cost savings for industries and reduce environmental impact. Energy consumption optimization in industrial robots is an essential aspect of green manufacturing, as it helps reduce the carbon footprint and operating costs of the manufacturing process. To optimize and reduce energy consumption in industrial robots, the idle time of industrial robots during working schedules can be minimized. The process involves programming the robot to switch off when it is not in use or reducing the time it spends in standby mode. By using a sleep mode or a power-saving mode during idle time of industrial robots, energy consumption can be optimized. Energy consumption of industrial robots can be reduced by modifying the path and motion of robots during working times to eliminate unnecessary movement. Another way to optimize energy consumption in working times of industrial robots is to use energy-efficient components and technologies, such as LED lighting and high-efficiency motors and controllers. lightweight materials in the construction of robots can be used in order to reduce the robot overall weight, which can reduce the amount of energy required to move robot components. it is also important to ensure that the robot is properly maintained and serviced, as this can help to prevent energy waste caused by faulty components or inefficient operations. Regular maintenance can ensure that the robot components are functioning optimally, reducing energy consumption. Performance of industrial robots can be improved by replacing outdated components for newer, more energy-efficient ones. Moreover, monitoring the energy consumption of industrial robots can help to identify areas of energy usage in order to be analyzed and optimized. This can be achieved by installing energy meters and using software tools to analyze the data. Also, various energy-saving features, such as regenerative braking system which converts kinetic energy into electrical energy are designed in industrial robots in order to enhance efficieny of energy usage in industrial robots. Industrial robot energy consumption can also be decreased by manufacturing process optimization, which also improves sustainability by lowering carbon emissions and energy costs. There are many exciting research directions in the optimization of energy consumption in industrial robots, and continued research in this area has the potential to lead to significant improvements in energy efficiency and sustainability in industrial settings. Here are some potential research directions in this area:

1. Adaptive control strategies: Developing adaptive control strategies that can adapt to changes in the robot's environment and task requirements can significantly reduce energy consumption. For example, if the robot is performing a task that requires less precision, it can be controlled with lower gains to reduce energy consumption.
2. Intelligent motion planning: Developing advanced motion planning algorithms that optimize energy consumption is essential. These algorithms should consider factors such as the robot's task, environmental conditions, and energy-efficient trajectories. Optimizing the robot's movements and reducing unnecessary actions can lead to significant energy savings.
3. Predictive maintenance: Implementing predictive maintenance strategies can help prevent unexpected breakdowns and optimize energy consumption. By monitoring and analyzing data from various sensors and components, predictive maintenance algorithms can detect potential failures or deteriorations in performance, enabling proactive maintenance actions to minimize downtime and energy waste.
4. Real-time monitoring and control: Developing robust monitoring and control systems that provide real-time data on energy consumption can enable operators to identify and address energy inefficiencies promptly. Real-time feedback can help optimize robot operation parameters, adjust control settings, and identify energy-saving opportunities during runtime.
5. Data-driven optimization: Leveraging data analytics, machine learning, and artificial intelligence techniques can enhance energy optimization in industrial robots. By analyzing large volumes of historical and real-time data, algorithms can identify patterns, optimize robot parameters, and provide actionable insights for energy-saving strategies.
6. Advanced modeling techniques: Developing advanced modeling techniques that can accurately predict the energy consumption of a robot can help optimize its energy usage. This can involve developing models that capture the dynamics of the robot and its environment, as well as models that predict the energy consumption of different components.
7. Energy-efficient hardware: Developing energy-efficient hardware components, such as motors and sensors, can reduce the overall energy consumption of industrial robots. Designing and manufacturing more efficient and lightweight materials can help decrease the energy required for robot movement and operation. This can involve exploring new materials, designs, and technologies that can reduce energy losses and increase efficiency.
8. Energy-aware scheduling: Efficiently scheduling tasks and operations in industrial robot systems is vital for optimizing energy consumption. Energy-aware scheduling algorithms should consider the energy requirements of different tasks, prioritize energy-efficient operations, and minimize idle times or unnecessary robot movements.
9. Sensor fusion: Integrating multiple sensors to provide a more comprehensive view of the robot's environment can help optimize its energy usage. For example, combining visual and tactile sensors can help the robot identify objects and adjust its movements to avoid collisions, which can reduce energy consumption.
10. Machine learning techniques: Applying machine learning techniques to optimize the energy consumption of industrial robots is a promising area for research. For example, using reinforcement learning to develop energy-efficient control policies can help robots learn how to optimize their energy usage over time.
11. Model-based optimization: One approach to optimize energy consumption in industrial robots is to build mathematical models that capture the behavior of the robot and its energy consumption. These models can be used to optimize the energy consumption by adjusting the control parameters of the robot, such as the velocity and acceleration. Future research could focus on developing more accurate models that capture the dynamics of the robot and its interactions with the environment.

12. Sensor-based optimization: Another approach to optimize energy consumption in industrial robots is to use sensors to monitor the robot's energy consumption and adjust the control parameters accordingly. For example, if the robot is performing a task that requires less force, the control system could reduce the torque applied to the motors, thus reducing energy consumption. Future research could focus on developing more advanced sensors and control algorithms that can dynamically adjust the robot's energy consumption in real-time.
13. Multi-objective optimization: Optimizing energy consumption in industrial robots is often a multi-objective problem, as there are often trade-offs between energy consumption, task completion time, and quality. Future research could focus on developing multi-objective optimization algorithms that can find optimal solutions that balance these trade-offs.
14. Human-robot collaboration: In many industrial settings, robots work alongside human operators. Future research could focus on developing energy optimization algorithms that take into account the presence of human operators and their interaction with the robot. For example, the robot could adjust its energy consumption based on the proximity of the human operator, ensuring that it operates safely and efficiently.
15. Energy storage and management: Future research could also focus on developing energy storage and management systems for industrial robots. Implementing intelligent power management systems in industrial robots can help optimize energy consumption. These systems can monitor energy usage, identify inefficient operations, and dynamically allocate power resources to minimize waste. Additionally, incorporating energy recovery mechanisms, such as regenerative braking or energy harvesting, can help capture and reuse energy that would otherwise be lost.

Overall, the optimization of energy consumption in industrial robots is an important area of research that has the potential to improve the energy efficiency of manufacturing processes and reduce their environmental impact.

Declaration of Competing Interest

I confirm that there is no conflict of interest regarding the submitted manuscript with title of Optimization of Energy Consumption in Industrial Robots, A Review to the Cognitive Robotics.

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