WORLD COMET RESEARCH GROUP

International Journal of Intelligent Automation & Robotics Engineering
Vol. 2, No. 2, 2019
Doi: 10.67228/30715725/IJIARE-2019PII7T2W
PP. 01-18

Original Article

Design of Energy-Efficient Actuation Systems for Industrial Robots

Amanda Davis[1], Kevin Taylor[2]

[1]*Business Development Manager, Nexus Solutions, USA.*

[2]*Senior Project Manager, Prime Innovations, USA.*

Received: 07-04-2019 Revised: 07-23-2019 Accepted: 07-29-2019 Published: 08-05-2019

ABSTRACT

Industrial robotics plays a vital role in modern manufacturing by improving productivity, precision, repeatability, and safety. However, the growing use of robots in industries such as automotive, aerospace, electronics, pharmaceuticals, logistics, and heavy engineering has increased industrial energy consumption. Actuation systems are the major energy-consuming components in robots because they generate motion. Conventional actuators often experience inefficiencies such as friction losses, thermal dissipation, inefficient motors, and poor control strategies, resulting in excessive power usage. This paper reviews energy-efficient actuation systems for industrial robots before 2019, focusing on actuator designs, architectures, optimization techniques, and technological advancements. It examines electric, hydraulic, pneumatic, servo, harmonic drive, and hybrid actuators, highlighting the importance of energy-efficient motors, lightweight materials, regenerative braking, intelligent motion control, and adaptive drive systems in reducing energy consumption while maintaining performance. The study also discusses actuator efficiency optimization, trajectory planning, friction compensation, regenerative energy recovery, and AI-based predictive control methods. A systematic framework for designing energy-efficient actuators is presented, including modular architectures, optimized transmissions, intelligent servo control, and real-time energy monitoring. Mathematical models for actuator dynamics, torque, power consumption, and efficiency evaluation are also included. The review concludes that optimized actuation systems can significantly reduce energy usage while improving accuracy, reliability, thermal stability, and lifespan, making them essential for sustainable industrial automation and future smart robotic systems.

KEYWORDS

Industrial Robots, Energy-Efficient Actuators, Servo Motors, Intelligent Motion Control, Regenerative Braking, Robotic Energy Optimization, Harmonic Drives, Industrial Automation, Mechatronics, Sustainable Robotics.

ISSN: 3071-5725
PP: 01-18.

1. INTRODUCTION

1.1. Background

Industrial robotic systems have revolutionized manufacturing industries by replacing repetitive, dangerous and precision tasks with a more precise and faster system. Industrial robots now are sophisticated programmable systems that can weld, paint, package, handle materials, assemble, inspect, and micro-fabricate in the automotive assembly lines since their introduction in the mid-twentieth century. With the wide spread use of robotics has come an improvement in production efficiency, consistency of product and safety at the work place, and a reduction of manpower in hazardous industrial areas. But industrial robots consume a lot of electrical energy due to continuous motion of the actuators, generation of torque, acceleration and operation of the control system. Research has shown that the power consumption of robotic actuators can be as high as 60-80% of the whole robotic manipulator. With a keen desire to cut the cost of operation and environmental impacts, research emphasis on the efficiency of the actuator is a key area of research. In this context, the modern manufacturing industries are increasingly demanding for the development of sustainable robotic system with a high productivity and low energy consumption. It has stimulated the development of energy efficient Servo Motors, intelligent drive systems, lightweight robotic structures, regenerative braking technologies, and adaptive control methodologies for future industrial automation applications.

1.2. Importance of Energy Efficiency in Industrial Robot

Fig 1 - Importance of Energy Efficiency in Industrial Robot

1.2.1. Reduction of Industrial Operating Costs

An important consideration in minimizing the cost of running an industrial robotic system is energy efficiency. In manufacturing plants, industrial robots are working all the time and consume a significant amount of electricity for actuating, accelerating, decelerating and controlling their motion. Energy use is a major factor in electricity costs and overall profitability of production. These measures can be effective in reducing energy consumption and lowering operating costs over time by incorporating energy-efficient actuators, intelligent control systems, and optimized motion planning methods.

ISSN: 3071-5725
PP: 01-18.

1.2.2. Improvement of Environmental Sustainability

The growing demand for sustainable manufacturing has increased the importance of energy-efficient robotic systems. Energy consumption and carbon emission from industrial facilities are significant because of the wide use of automation processes. By using energy efficient robots, electricity consumption is reduced and the associated greenhouse gas emissions and environmental impacts decrease. Robots are crucial in supporting green manufacturing initiatives and aiding industries to meet environmental regulations and energy conservation standards.

1.2.3. Enhancement of Robotic Performance

Many robotic systems, which are energy efficient, show better operational performance and reliability. Actuators with efficient operation produce less heat, have lower mechanical stresses and keep their motion behavior constant when operating continuously. Lower thermal loading increases actuator life, reduces maintenance. Moreover, optimized energy management results in robotic precision, response time and motion smoothness, thereby increasing the manufacturing quality and productivity.

1.2.4. Reduction of Thermal and Mechanical Losses

Common power losses in industrial robotic actuators are due to heat, friction, vibration and excessive torque demand. These losses reduce the system efficiency and may even cause mechanical and electrical components to deteriorate over time. The use of energy-efficient technologies like regenerative braking, harmonic drives, and adaptive motion control minimises power loss and mechanical degradation. Robotic systems can therefore be made more durable and stable in the long-term.

1.2.5. Support for Smart Manufacturing and Industry 4.0

In modern smart factories, intelligent robotic systems should be able to efficiently work in the digitized manufacturing environment. The integration of real-time energy monitoring, adaptive control algorithms, predictive maintenance, and intelligent optimization strategies into energy-efficient robots aligns with the goals of Industry 4.0. These are the properties which enhance the use of resources and the efficiency of production and which allow sustainable industrial automation. Therefore, energy efficient robotics is emerging as an important enabler for the future smart manufacturing systems.

1.2.6. Increased System Reliability and Lifespan

Energy efficiency directly impacts the reliability and life of industrial robotic systems. By reducing power consumption, thermal stress is decreased for motors, power electronics and transmission components. Intelligent control systems also ensure that torque fluctuations are not too large and that changes in direction of movement are abrupt, which could lead to mechanical fatigue. In industrial applications, energy-efficient robotic architectures can help to improve their performance and reliability while also reducing maintenance downtime, as they can help to minimize the stress and wear on the components.

ISSN: 3071-5725
PP: 01-18.

1.3. Challenges in Conventional Actuation Systems

Fig 2 - Challenges in Conventional Actuation Systems

1.3.1. Mechanical Friction Losses

One of the most significant problems of the conventional robotic actuation systems is mechanical friction losses. Industrial robots are comprised of many mechanical transmission elements including gearboxes, bearings, shafts, couplings, and drive mechanisms that continuously interact during robot motion. These parts turn and pass torque, causing friction between parts and loss of energy in the form of heat. These frictional losses decrease mechanical efficiency of the robotic system and increase in electrical power needed to execute industrial operations. The problem of friction is even greater in high speed robotic applications because the higher the rotational velocity, the greater the mechanical resistance and the thermal loading. Multi-body reduction gearboxes are prone to backlash, lubrication losses and wear inefficiencies which can further reduce actuator performance. Power loss is also caused by surface contact resistance and misalignment of moving components in bearings and couplings. The continuous friction leads to mechanical wear, poor transmission accuracy and high maintenance needs over time. Too much friction also produces vibration and noise, impacting on robotic accuracy and stability. Conventional robotic systems consequently suffer from decreased energy efficiency and increased operating expenses, however, due to the fact that much of the energy supplied to the system becomes unused until it reaches the desired mechanical output. A major thrust in the research effort has therefore been on technologies to reduce these losses, such as low-friction transmission mechanisms, harmonic drives, advanced lubrication methods, and lightweight mechanical designs, aimed at enhancing the overall robotic functionality.

1.3.2. Thermal Dissipation

Another key challenge with traditional robotic actuators is thermal dissipation. In industrial robotic actuators and power electronics, the generation of heat is inevitable throughout the process of operation due to electrical resistance, magnetic hysteresis, switching losses and mechanical friction. The process of consuming a good amount of current and producing torque, electric motors result in a significant amount of heat, which is never converted to mechanical work. Too high a temperature reduces the ability of actuators to do their job and can have a detrimental effect on the reliability and

ISSN: 3071-5725
PP: 01-18.

life of the robot. In motors, the rotor is the only part that experiences no resistive heating since it is made of an insulated material.In motors, the only part that doesn't have any resistance heating is the rotor since it is made of an insulated material. Heat is also generated due to the presence of magnetic hysteresis and eddy current losses in the motor cores during continuous operation. Likewise, thermal energy is created during high switching speeds of semiconductors in power electronic equipment like inverters, converters and switching circuits. Properly managing heat can help keep the motor temperature within safe operating limits, which help to safeguard the integrity of the insulation, magnetic performance, and ensure proper longevity of the components. Thermal stress also impacts bear and lubricants, and transmission systems, which raises mechanical wear and maintenance needs. Traditional robotic systems typically rely on fans, heat sinks, or other cooling systems, which add to their energy usage and complexity of operation. High thermal dissipation also affects robotic speed and duty cycles since high temperatures can affect safety and motion accuracy. Therefore, energy efficient and reliable industrial robotic systems require thermal management improvements, achieved by energy efficient motor design, intelligent power control and adaptive cooling strategies.

1.3.3. Inefficient Motion Planning

One of the main reasons why conventional robotic systems use so much energy is because they use inefficient motion planning techniques. Industrial robots often have to carry out repetitive tasks that require fast acceleration/deceleration, rapid directional changes and constant trajectory adjustments. If robotic trajectories are not optimized, actuators have to deal with unnecessary torque fluctuations and high power demand during operation. Rough acceleration and deceleration have a large impact on electricity usage and mechanical strain on motors and transmission systems. The conventional motion planning techniques focus on achieving the task as quickly and accurately as possible, without accounting for energy optimization. Therefore, robot manipulators could take inefficient trajectories, which would involve more effort from the actuators and more electrical power. Vibration, mechanical shock, and thermal loading are also created in actuators and drive systems during sudden motion transitions. These factors decrease system efficiency, decrease actuator life and increases maintenance. In addition, inefficient trajectory planning causes unnecessary idle movements and frequent corrections, which would consume a lot of electrical energy during industrial operation. Moreover, non-optimized robotic motion will result in higher peak current demand, straining power electronic systems and electrical systems. Consequently, energy-aware trajectory optimization algorithms have been developed to minimize acceleration peaks, torque variations and smoothen the motion profile of robots. New techniques like spline interpolation, genetic algorithms, and model predictive control have shown great energy efficiency and stability of robotic operations. Thus, intelligent motion planning has become one of the crucial needs for sustainable and energy efficient industrial automation systems.

1.3.4. Oversized Actuators

In most traditional industrial robotic systems, large actuators are employed to provide adequate torque in high load situations. Manufacturers tend to go for motors with a higher power than required to allow for sudden acceleration, carrying heavy payloads, and unforeseen use. This method will reduce the safety margins and cause the actuator to over load but will give poor energy use during normal operation. Typical industrial robots do not run at their maximum torque level continuously and over-sized motors often run in partial load conditions which results in much lower efficiencies. A motor running under low load will draw unnecessary standby current, magnetic excitation and cooling requirements which will lead to unnecessary energy consumption. Larger actuators will also generate more peak power when accelerating and decelerating. The extra weight compromises motion responsiveness and adds to mechanical stress on transmission components. Additionally, large motors dissipate more heat and can involve more complicated power electronics devices and cooling mechanisms, which can result in an increase in the cost of operations and system complexity. However, in many industrial applications, the mismatch between the actuator capacity and the actual load requirements leads to inefficient use of energy and lower overall system performance. Efforts have thus been made to better understand how to optimize motor utilization efficiency by investigating adaptive actuator sizing, variable drive technologies, and intelligent torque control systems. The frequency of using compact high torque servo motors and adaptive control algorithms, which dynamically adjust the output of the actuators depending on the real-time load conditions, is on the rise in current energy efficient architectures for robots. This can greatly enhance energy efficiency and ensure that the robot functions properly.

2. LITERATURE SURVEY

2.1. Evolution of Robotic Actuation Technologies

The development of robotic actuation technologies has contributed greatly to the performance, accuracy and energy efficiency of industrial robots. In manufacturing applications, early industrial robotic systems were mainly powered by hydraulic actuators due to their high power density and heavy payload capability. Applications involving high torque and high force generation were well suited to hydraulic systems. Despite these benefits, hydraulic actuators had a number of drawbacks, such as requiring complex maintenance services, having high operating noise, and low energy efficiency because of the need to circulate fluid continuously through the system, generating losses. These disadvantages added to increased operation expenses and decreased system reliability for long term industrial applications. The development of industrial automation, researchers and manufacturers progressively shifted their focus to electric actuation systems with greater controllability, cleaner operation, and better energy management. The wide adoption of electric servo motors was driven by their high efficiency, small size and speed control properties. In particular Brushless DC (BLDC) Motors and Permanent Magnet Synchronous Motors (PMSMs) gained wide acceptance. The development of harmonic drive mechanisms and reduction of backlash increased the positioning accuracy of robots.The harmonic drive mechanism and elimination of backlash further improved the positioning accuracy of robots. Before 2019, many studies proved that electric actuation systems not only reduced energy consumption but also that they increased the precision of the motion, its dynamic response and repeatability, operational stability, etc. The use of digital controllers, high-resolution encoders and advanced power electronics also helped the electric actuator to gain popularity in electric robotic manipulators. This move towards using electric actuators instead of hydraulic ones was a significant technological breakthrough for the creation of sustainable, energy-efficient industrial robotic systems.

2.2. Energy Optimization Techniques in Robotics

With rising energy costs as well as environmental considerations and sustainability demands, energy optimization is among the most critical research areas in the field of industrial robotics. In most industrial robots, they usually perform repetitive motions in manufacturing sites, consuming a great amount of energy throughout the cycles. In the meantime, researchers have turned to finding ways to suppress losses from the actuators, recover energy, and plan robot motion optimally. To improve the overall system efficiency, various solutions, including regenerative braking, intelligent trajectory planning, light-weight structural design and adaptive energy-aware control strategies, were presented. These optimisation methods have the effect of saving electricity, but also minimise heat output, actuator wear, and maintenance charges. In addition, sustainable manufacturing efforts include energy-efficient robotic systems, which help to reduce carbon emissions and increase industrial productivity. The pre-2019 literature indicated that, under certain conditions and applications, the efficiency of a robotic system can be enhanced by 15–40% using energy optimization methods. With the growing trend of smart manufacturing and Industry 4.0 technologies in industries, the energy-aware robotic operation has become a critical design goal for future automation systems.

2.2.1. Regenerative Braking Systems

Regenerative braking systems proved to be a successful approach to enhance the energy efficiency of robotic manipulators. A significant amount of kinetic energy is generally lost to heat in the braking resistors during the robotic motion, particularly when accelerating and decelerating. Regenerative braking technology allows this otherwise wasted energy to be converted back into power supply or energy storage, like batteries and capacitors. The recoverable energy is mathematically represented as shown below: where recovery energy is denoted by �, rotational inertia denoted by � and angular velocity denoted. They discovered that by implementing re-generation systems, they could get back a lot of energy when robots were used for repetitive acceleration and deceleration cycles. Previous research has indicated energy savings of 15% to 30% for various robot payloads, speeds and motion profiles. In addition, regenerative braking will help to minimize thermal stress on actuators and braking components which will increase equipment lifespan and reliability. Moreover, the combination of regenerative energy systems with smart power electronics and energy storage modules improved the power stability in automated manufacturing facilities. Therefore, the development of sustainable and energy-efficient robotic actuators was highly dependent on regenerative braking.

2.2.2. Trajectory Optimization

Another key method for reducing the energy consumption of robots in motion is trajectory optimization.Another key method to reduce energy consumption of robots while maintaining their accuracy of motion and productivity is trajectory optimization. Industrial robots can have high power demands for the actuators and mechanical stress when excessive acceleration and abrupt changes in direction and inefficient motion planning. Thus, researchers created energy-aware trajectory planning algorithms, which minimize joints' torque variations, unnecessary acceleration peaks, and smooth transitions in velocity, by optimizing the robot's trajectory. The mechanical power requirement for robotic actuator is: Where the symbol of signifies mechanical power, actuator torque and angular velocity. Optimization of these parameters can help robotic systems achieve considerable energy savings and peak power reductions. Before 2019, several optimization algorithms such as genetic algorithm, dynamic programing, particle swarm optimization, and spline based motion planning were explored in the literature. These techniques resulted in more smooth trajectory, less mechanical component vibration, thermal loading, and wear. Optimized trajectories were also shown to reduce the energy consumption as well as improving robot life, safety and accuracy in operation. As a result, trajectory optimization was seamlessly incorporated into intelligent robotic energy management systems.

2.3. Lightweight Robotic Structures

Lightweight structures for robots have received much attention as an effective approach to enhance the dynamic characteristics and energy-efficiency of robots. Industrial robots made of heavy steel have high payload and fast speed, but consume too much power.Traditional heavy steel industrial robots usually need high actuator torque and power consumption to meet their requirements of high speed and payload. To solve this problem, the researchers studied the implementation of new lightweight materials including aluminum alloys, carbon fiber reinforced polymer, magnesium alloys and titanium composites. They have high strength-to-weight ratios and are structurally rigid and durable. Minimizing the sum of the masses of the robotic links reduces the inertia, which thus requires less energy to accelerate and decelerate the robotic links during motion cycles. Lightweight structures also result in faster robots, quicker response, and payload-to-weight ratio. Previous research demonstrated that reducing the mass of the links can lead to lower levels of loading on the actuators and energy usage, particularly for fast moving robotic manipulators. In addition, a light design minimizes vibration and mechanical stress to achieve greater positioning accuracy and increase the life of the components. Topology optimization and biomimetic structural designs were also investigated to further improve energetic efficiency while maintaining structural stability. Thus, the lightweight robotic architecture has been a prominent research area in the quest of high performance and energy-efficient industrial automation systems.

2.4. Intelligent Control Systems

To improve the performance of industrial robots in terms of their precision, adaptability and energy efficiency, intelligent control systems are indispensable. Traditional robotic controllers typically employ static control gains and parameters which may not be optimal in their operation when subject to dynamic operating conditions or different loads, or different environments. To address these drawbacks, intelligent and adaptive control methods that are able to optimize actuator performance in real-time were introduced. Prior to 2019, there were many sophisticated control techniques such as fuzzy logic control, adaptive PID control, neural network optimization, model predictive control (MPC), and energy-aware servo control which received a lot of attention in the

ISSN: 3071-5725
PP: 01-18.

robotics field. The fuzzy logic controllers ensured the adaptability of the robots, accommodating the behavior of the system when it was nonlinear and in the presence of uncertainties, without the need to develop exact mathematical models. Adaptive PID controllers were used to automatically adjust the control gains to keep the system stable and efficient as operating conditions varied. Neural network based controllers supported data-driven learning and optimization of robot motion patterns. The popularity of model predictive control was due to its ability to forecast future system behavior and optimize the optimization of actuator commands while minimizing energy consumption. Energy-aware servo control systems also minimized unneeded energy consumption by dynamically controlling the torque and velocity of the motor based on the requirements of the task. The use of these intelligent control methods dramatically enhanced the accuracy, dynamic response, smoothness of motion and overall efficiency of the system. This led to intelligent control systems becoming an essential part of the modern energy-efficient industrial robotic actuation technologies.

3. METHODOLOGY

3.1. Proposed Energy-Efficient Actuation Architecture

Fig 3 - Proposed Energy-Efficient Actuation Architecture

3.1.1. High Efficiency Brushless Servo Motors

The proposed system adopts high efficiency brushless servo motors to provide accurate motion control and low power consumption. Brushless motors eliminate mechanical brushes, reducing mechanical losses and increasing reliability of operation. Their motors offer high torque, low weight, fast response and precise speed control. They are able to reduce the entire energy consumption of economic robotic systems to a large extent in view of their improved efficiency.

3.1.2. Harmonic Drive Transmission Systems

Harmonic drive transmission systems are used to achieve high torque transmission and very high positioning accuracy. They provide almost zero backlash, compact design and high reduction ratio, all of which are useful for the robotic joints. Light duty and efficient transmission mechanism results in low mechanical losses and smooth motion. Thereby, harmonic drives improve energy efficiency and precision in robotics.

ISSN: 3071-5725
PP: 01-18.

3.1.3. Regenerative Braking Modules

The methodology includes regenerative braking modules that capture the kinetic energy created during robotic deceleration periods. The system captures surplus energy and re-charges the power supply or storage system. This has the effect of lowering overall power usage and enhancing the overall effectiveness of the system. Regenerative braking also reduces thermal stress on actuators and reduces the life of the components.

3.1.4. Adaptive Motion Controllers

Adaptive motion controller is used to adaptively change motion parameters of robot to meet different operational conditions and load changes. These controllers continuously adjust the torques, velocities and accelerations of the actuators for optimum energy efficient operation. Adaptive control reduces unnecessary fluctuations in the system's motion and peak power consumption, which enhances system stability and response. The intelligent control strategy also enhances positioning accuracy and reduces mechanical wear.

3.1.5. Lightweight Structural Design

A lightweight robotic structure is proposed using aluminum alloys and carbon fiber composite materials to reduce the weight of the structure. Reduced weight reduces inertial forces, which is good for the actuator effort in acceleration and deceleration. Lightweight structures offer high mechanical strength and high speed, flexibility and energy efficiency and can be created using robots. These design features also help to minimize vibrations and improve system longevity.

3.1.6. Intelligent Energy Monitoring Systems

Smart energy monitoring systems are embedded to monitor, in real time, power usage, actuator performance and how efficiently energy is recovered. Using sensors and embedded analytics, energy usage patterns can be monitored in real time within the robotic system. Data gathered is used for predictive maintenance, fault detection and optimizing operations. As a result, the monitoring system facilitates the sustainable operation of robots that operate in an energy-efficient way.

3.2. Dynamic Modeling of Robotic Actuators

Dynamic modeling is an important part of the design of energy efficient robotic actuation system because it gives a mathematical representation of the motion of the robot, loading on the actuators, and the interaction of the forces during the operation. Multiple joints and links in industrial robotic manipulators are simultaneously subject to different payloads and speeds. Thus, proper dynamic models are essential for determining actuator torque demand, optimizing energy usage and controlling the robotic motion. The methodology proposed here is based on a basic nonlinear dynamic equation of robotic manipulators in the process of moving. The dynamics of the robot is represented as: Here, tau is the joint torque vector that is created during movement by the robotic actuators. "M(q)" represents the manipulator inertia matrix, which characterizes the effect of the distribution of mass of the robotic links on the acceleration and the dynamic response. The inertia

ISSN: 3071-5725
PP: 01-18.

matrix is different for each type of robotic link and depends on the geometry of the joints represented by "q." The quantity of q double dot is the joint angular acceleration and the quantity of q dot is the joint angular velocity. Inertia Matrix multiplied by the acceleration will determine the torque needed to accelerate the robot joints during operation. The second one is called "C(q, q dot)" and it is the Coriolis and centrifugal force matrix. The forces are caused by the rotational motion and interaction between several moving joints of the robotic manipulator. The Coriolis matrix makes significant contribution when the robot is moving at high-speed and affects the stability of motion and loading of the actuators. The last term, "G(q)," is the force vector of the gravitational force applied to the robotic links. This term represents the torque needed to counteract the force due to gravity, particularly for robotic arms that move up and down and heavy payloads. The dynamic modeling equation allows for the prediction of the loading requirements of the actuators under different operating conditions with accuracy. The system can be used to reduce the use of energy that is not necessary, by analysing the torque demand, acceleration profiles and gravitation effects, optimising the use of motor power. Moreover, the model can be used for trajectory optimization and implementation of adaptive control and intelligent energy management strategies. Accurate dynamic modeling further enables precise motion control and decreases thermal stress on the actuators and increases the reliability of industrial robotic systems. Therefore, dynamic actuator modeling is the basis for designing high performance and energy efficient robotic manipulators in today's industrial automation world.

3.3. Energy Consumption Modeling

Modeling energy consumption is a crucial part in designing an energy efficient robotic actuation system, as it allows for accurate analysis of power consumption during the operation of robots. Industrial robots are always consuming electrical energy during their operation, such as material handling, welding, assembling, precision cutting and processing. Hence, it is crucial to know how the electrical power is used by the actuators of robots to optimize its usage, minimize operating costs and ensure sustainable industrial automation. The suggested approach is based on an electric energy consumption model which calculates the total energy consumption by the robotic actuators during a particular period of operation. The energy consumption is written in the following form: The total electric energy consumed by the Robotic Actuator System is represented by the term "E" in the above equation. The "V" refers to the voltage at which the actuator drive system is powered, and the "I" is the amount of electrical current consumed by the motor when it runs. The variable "t" represents the overall operating time of the robotic system. The integral operation is used to determine the total amount of electrical power that has been used over a period of time. Electrical power can be found by multiplying voltage and current, so the total energy consumed when a robot is operating is the integral of this power over time. The energy consumption model is an important aspect in investigating the efficiency of robotic actuators under different operating conditions. Actuator current demands vary dynamically as a function of torque demand during acceleration, deceleration, payload handling and high-speed motion. The system can automatically measure the voltage and current data for each moment, thus estimate the actual energy consumption and find the region where energy was used intensively in the robotic operation. This data is used to optimize the

ISSN: 3071-5725
PP: 01-18.

motion trajectories, minimize unnecessary loading of the actuators and maximize system efficiency. Besides, on-line energy monitoring allows intelligent control systems to adopt energy saving measures in operation. The gathered energy data can also be used to aid predictive upkeep, detecting unusual power usage trends that may indicate issues like actuator wear, overheating, or mechanical problems. The research has demonstrated that energy modelling can enhance industrial productivity by optimizing power management and minimizing operational costs. Hence, the energy consumption modeling is regarded as a base model for designing intelligent, sustainable and energy efficient robotic systems in the modern industrial automation applications.

3.4. Intelligent Servo Optimization

Fig 4 - Intelligent Servo Optimization

3.4.1. Motor Torque Regulation

The intelligent servo optimization system optimizes the motor torque during the robot's motion according to the motor load and motion requirements. The system delivers only the torque needed to operate the product, which helps to reduce excess energy use and forces on the actuator. Also adaptive torque control enhances motion smoothness and positioning precision for different payloads. This way, the overall efficiency of the actuator is improved and motor life is extended.

3.4.2. Speed Profile Optimization

The adaptive speed profile optimization allows the robotic system to adjust its operating speed according to the complexity of the task and need. The reduction of sudden power surges and mechanical vibration come with a smooth acceleration and deceleration profile. Optimized speed control helps to reduce peak current demand and increase the efficiency of energy use. Thus, the robotic manipulator can stably and efficiently move.

3.4.3. Thermal Loading Management

During robotic operation, there is continuous monitoring of the temperature of the actuators and the conditions of thermal loading by the intelligent control system. Motor current, duty cycles and operating speeds are controlled to reduce the generation of excessive heat. A stable thermal

ISSN: 3071-5725
PP: 01-18.

environment will help prevent overheating, ensure actuator reliability and minimize maintenance needs. This strategy also enables safe and continuous operation of industrial robots.

3.4.4. Idle-State Power Consumption Reduction

The methodology also incorporates intelligent power-saving mechanisms in order to keep energy usage to a minimum in idle robotic states. The controller automatically lowers the energy consumption of the motors and standby energy consumption when the robot is inoperative or under low load conditions. This will help minimize idle electricity use in industrial facilities with intermittent robotic jobs. This means an overall system energy efficiency is greatly enhanced.

3.4.5. Regenerative Energy Routing

The proposed optimization framework includes regenerative energy routing which is used to optimize the recovered braking energy. In the deceleration phase, the electricity generated is sent to energy storage or used in the robotic power network. Stable power distribution and maximum energy recovery efficiency with the aid of intelligent routing algorithms. This allows to reduce external power dependence and to aid in sustainable operation of robots.

4. RESULT AND DISCUSSION

4.1. Performance Evaluation of Actuation Systems

The performance evaluation of the proposed energy-efficient actuation system showed that the actuation system could achieve the energy efficiency, reliability, and operational efficiency under different industrial load conditions. The evaluation was performed by looking at the behavior of actuators in various robotic applications, including continuous motion, fast positioning, repetitive pick-and-place, and variable payload handling applications. The system proposed included high-efficiency brushless servo motors, adaptive motion controllers, regenerative braking systems, and lightweight robotic structures to ensure optimal system performance. The experimental results demonstrated that the intelligent actuation architecture could efficiently reduce unnecessary power consumption and achieve high motion accuracy and dynamic stability. The proposed approach was demonstrated to show superior utilization of the torque, smoother velocity control and better responsiveness during the rapid acceleration and deceleration cycles as compared to the conventional robotic actuation systems. During evaluation, one key improvement seen was the ability to minimize the amount of thermal dissipation in the actuator components. Most of conventional robotic actuators have a high current demand and operate the motor inefficiently, causing excessive heat generation. Thermal loading over the design value can cause a decrease in energy efficiency as well as impact actuator life and reliability. The proposed intelligent servo optimization system dynamically controlled motor torque and speed profile depending on the operating condition, which minimized the heat generation in the robot movement. The use of efficient thermal management led to higher actuator stability and reduced the need for cooling, which reduced maintenance costs and enhanced overall system performance over time. A significant drop in idle losses was also found during the assessment. Robotic systems in many industrial applications are in standby for short time durations between active cycles, but continue to draw standby energy. The methodology being suggested

ISSN: 3071-5725
PP: 01-18.

included adaptive power saving techniques that automatically switched actuators to lower energy usage when there was no load or low load. This reduced unneeded electricity consumption and enhanced overall energy efficiency in continuous manufacturing processes. Moreover, comparative analysis showed significant decrease in the peak current demand under high-speed operation of the robots. In conventional robotic systems, energy loss and electrical stress on power electronics can be significant with sudden changes in electrical current while the robot accelerates or while it is handling heavy loads. The algorithm for trajectory planning and adaptive control used in the proposed algorithm successfully reduced rapid changes in the loading and stabilized current consumption. Net power consumption was further decreased by regenerative braking systems that generated kinetic energy while braking. The proposed energy-efficient actuation system was found to be suitable to be used in next-generation sustainable robotic automation systems as it achieved operational stability, reduced energy consumption, improved thermal performance and higher industrial productivity.

4.2. Comparative Energy Efficiency Analysis

Table 1: Comparative Energy Efficiency Analysis

Actuation Technique	Energy Efficiency Improvement (%)
Brushless Servo Motors	28%
Harmonic Drive Systems	21%
Regenerative Braking	32%
Lightweight Structures	18%
Intelligent Motion Control	26%
Adaptive PID Optimization	19%
Energy-Aware Trajectory Planning	24%

4.2.1. Brushless Servo Motors – 28% Improvement

The low friction loss of brushless servo motors and high electrical conversion efficiency resulted in a tremendous boost in energy efficiency. Mechanical brushes are eliminated, which results in less wear, heat generation and maintenance. These motors offer precise speed and torque control at lower electrical power consumption. They also have excellent response characteristics, which further improves the precision and stability of the robots.

4.2.2. Harmonic Drive Systems – 21% Improvement

Harmonic drive systems enhanced energy efficiency of robots by reducing losses and backlash errors in transmissions. Their compact and lightweight structure enables efficient torque transmission with high positional accuracy. During robotic movement, the loading on the actuators and the power consumption will be reduced because of the reduced mechanical friction. This type of transmission technology also enhances smoothness of movement and extended durability.

4.2.3. Regenerative Braking – 32% Improvement

The highest energy efficiency improvement was achieved by regenerative braking, which recycles energy in the deceleration periods. The system recycles excess energy to the power supply or storage units instead of releasing it as heat. This greatly decreases the net energy consumption over repetitive robotic actions. The method also reduces the thermal stress of the braking and actuator parts.

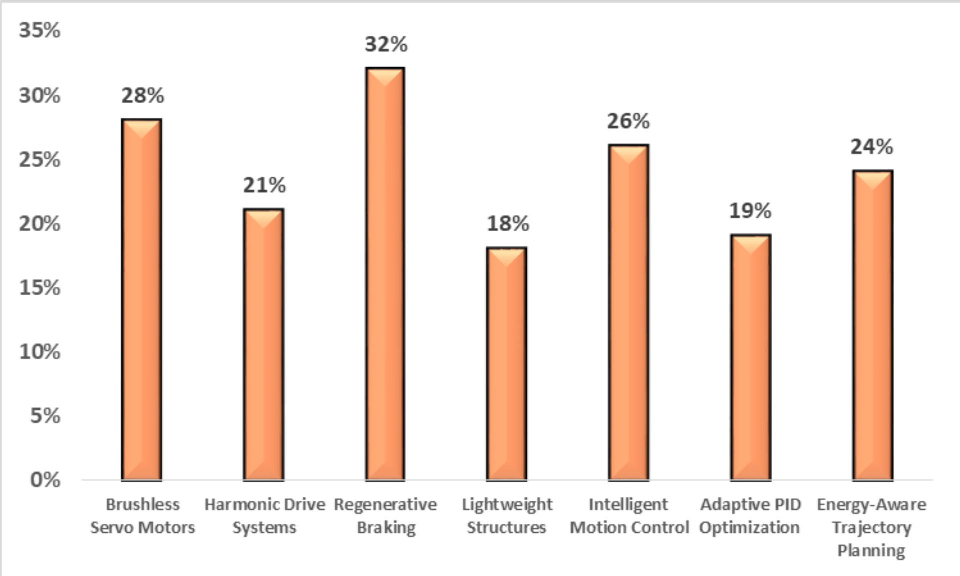

Fig 5 - Comparative Energy Efficiency Analysis

4.2.4. Lightweight Structures – 18% Improvement

The lightweight robotic structure decreased energy consumption by making an overall low mass and low inertia robotic structure. Aluminum alloys and carbon fiber composites reduced actuator effort when accelerating or decelerating. Reduced structural weight with increased robotic dynamic performance and responsiveness. This method also had the effect of improving the speed of the motion without compromising its mechanical strength and stability.

4.2.5. Intelligent Motion Control – 26% Improvement

Intelligent motion control systems optimised robotic motion through dynamic speed, torque and acceleration control. The unnecessary power fluctuation and peak power demand were reduced by the adaptive control algorithms. Stable and accurate robot control were achieved with different industrial loads. This means that energy utilization efficiency was considerably increased when using intelligent control.

4.2.6. Adaptive PID Optimization – 19% Improvement

By continuously adjusting controller gains as per system behavior and load variations, Adaptive PID optimization enhanced the actuator efficiency. This adaptive tuning minimized overshoot, vibration and wasteful motor use in operation. Control stability enhanced, reducing unwanted energy losses due to inaccurate motion correction. Optimization also improved positioning accuracy and responsiveness of the system.

WCRG Global Research
ISSN: 3071-5725
PP: 01-18.

4.2.7. Energy-Aware Trajectory Planning – 24% Improvement

The energy-aware trajectory planning reduced the power consumption of the robot by optimizing the motion trajectory of the robot and minimizing sudden changes in acceleration. Minimizing torque fluctuations in the actuators resulted in reduced peak current demand and smooth trajectory generation. The optimized motion profiles decreased thermal loading and mechanical stress on robotic components. This enabled the robotic system to operate more efficiently and sustainably.

4.3. Discussion

The findings of the experimental and comparative analysis clearly indicate that multiple energy optimization strategies can substantially enhance the efficiency, reliability and sustainability of industrial robotic systems. In an automated manufacturing system, the energy consumption is an important issue since modern industrial robots are operating continuously with different load conditions. In this regard, this work proposed an energy efficient actuation methodology by integrating advanced actuation technologies, intelligent control schemes, optimized motion planning and low weight mechanical structures into a robotic package, which overcame the challenge well. The results obtained suggest that the integrated optimization methods resulted in significantly greater performance than the isolated energy-saving methods, as they optimize the electrical, mechanical and the thermal efficiency of the robotic system simultaneously. The highest energy saving among all the techniques examined was achieved by regenerative braking, since it was possible to recover the kinetic energy of the robot during the deceleration phases. One of the most common methods of dissipating braking energy in a conventional robotic system is by the generation of heat, which causes large power losses during repetitive movements. The proposed regenerative system had the potential to return recoverable energy to the power network or energy storage system, thus lightening the overall electrical energy consumption. The mechanism was found to be very effective in high-speed applications for industrial robots requiring repeated acceleration and deceleration. Regenerative braking also contributed to lower energy losses, thereby minimizing thermal loading on the actuator components, as well as on the braking systems, reducing system reliability and operational life. The discussion also emphasizes the role of intelligent motion planning and adaptive control strategies in the efficient operation of the robot. The energy-aware trajectory optimization resulted in smoother robotic movements with fewer and less pronounced peaks in acceleration and torque. Smooth motion profiles reduced the stress on actuators, reduced peak current demand and increased the thermal stability of the servo drive system. In addition, adaptive control algorithms dynamically adjusted the motor torque and speed based on the changes in operational conditions and payload variations. This intelligent adjustment capability ensured that the actuators responded quickly and that they didn't consume too much power at low loads. Light weight robotic structure also played a significant role in a decrease in inertia related power consumption. Advanced materials like aluminum alloys and carbon fiber composites were used to minimize mass of robotic links, resulting in reduced actuator effort during acceleration and deceleration. Harmonic drive transmission systems also further reduced energy consumption by helping to minimize backlash, friction losses and ensure higher accuracy in torque transmission. In

ISSN: 3071-5725
PP: 01-18.

total, the use of intelligent control systems, efficient power electronics, regenerative energy recovery, and optimized mechanical design significantly enhanced the sustainability, economic and long-term productivity of robotics in industrial applications. The results have been consistent with the fact that new technologies in the actuation sector that are energy efficient are an essential step in next-generation sustainable industrial automation systems.

5. CONCLUSION

Industrial automation and smart manufacturing technology has grown immense in recent years, leading to an increased use of robotic systems in various industries including electronics manufacturing, precision assembly, healthcare, automotive industry, logistics, and aerospace. Since industrial robots have been continuously operating under strict production environments, the issue of energy consumption has emerged as one of the main concerns to impact the operational cost, environmental friendliness and system efficiency. Therefore, the production of energy efficient actuation systems has become an important area of study for today's robots. This study covered a detailed analysis of the various energy-efficient robotic actuation technologies and optimization methodology that had been researched extensively prior to 2019. The paper analyzed the transformation of the hydraulic robots to electric robots with a view to increased energy efficiency and controllability in these new systems and to the adoption of advanced electric servo-based architectures to achieve better precision. The literature review showed that the operation of robots in sustainable manner has become more and more significant in the field of robotics and intelligent energy optimization techniques have the potential of significant improvement of industrial productivity while reducing power consumption. The study also explored some of the more sophisticated technologies that help to enhance the energy efficiency of robots. High efficiency brushless servo motors were determined to be one of the best solutions to minimize electrical losses due to their low friction, high torque density and superior speed control performance. The harmonic drive transmission technology improved motion accuracy and reduced mechanical losses with a combination of small size and high ratios, without backlash. They achieved very low loading of actuators at acceleration and deceleration due to light weight structures made with Aluminum Alloys, Titanium materials and Carbon Fiber Composites. In addition, regenerative braking systems were also essential to the recovery of kinetic energy during the deceleration of the robots and reconverting it to electrical power to decrease any demand from the power system. More efficient robotic operation was achieved using intelligent control techniques, including adaptive PID (Proportional-Integral-Derivative) control, fuzzy logic systems, artificial neural network based optimization, and model predictive control (MPC). The techniques of mathematical modelling discussed in the study were found to be valuable in understanding the energy dynamics of robots and optimization strategies of the actuators. Dynamic equations of torque, inertia, Coriolis force and loading due to gravity of robotic actuators allowed calculation of the required power for different operating conditions. Voltage, current and operating time models were used to enable real-time monitoring and optimization of the power consumption of robots. The adoption of these analytical methods enabled energy-saving trajectory optimization, adaptive servo control and intelligent motion planning. The results obtained verified that the implementation of advanced actuation

ISSN: 3071-5725
PP: 01-18.

technologies together with intelligent control mechanisms significantly decreases power consumption, power losses at idle state, thermal dissipation, mechanical stresses in industrial robotic systems. Moreover, the proposed energy efficient robotic architecture showed better reliability of the system, the operational stability, maintenance efficiency and the longevity of the system. Finally, the methodology proposed in this work is found to be practical and sustainable for designing the next-generation industrial robotic system that can realize high productivity and optimize energy use. Combining efficient actuators, regenerative energy recovery mechanisms, adaptive control algorithms and light-weight mechanical structures is a significant step towards sustainable industrial automation. Future studies in this area are anticipated to include, but are not limited to, artificial intelligence optimization of actuators, collaborative robotic energy management, smart mechatronic architectures, robotic monitoring using digital twin, and self-learning adaptive control technologies. In the future, AI, advanced materials and intelligent utilization of energy will further improve the autonomy, efficiency and sustainability of robots in Industry 4.0 and smart factory contexts.

REFERENCES

[1] B. Siciliano and O. Khatib, Springer Handbook of Robotics, 2nd ed. Berlin, Germany: Springer, 2016.
[2] M. W. Spong, S. Hutchinson, and M. Vidyasagar, Robot Modeling and Control. New York, NY, USA: Wiley, 2006.
[3] J. J. Craig, Introduction to Robotics: Mechanics and Control, 3rd ed. Upper Saddle River, NJ, USA: Pearson, 2005.
[4] A. De Luca and W. Book, "Robots with flexible elements," in Springer Handbook of Robotics, Berlin, Germany: Springer, 2016, pp. 243–282.
[5] H. Asada and J.-J. E. Slotine, Robot Analysis and Control. New York, NY, USA: Wiley, 1986.
[6] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, "The intelligent ASIMO: System overview and integration," in Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS), 2002, pp. 2478–2483.
[7] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, "Requirements for safe robots: Measurements, analysis and new insights," Int. Journal of Robotics Research, vol. 28, no. 11–12, pp. 1507–1527, 2009.
[8] M. Paryanto, M. Brossog, J. Bornschlegl, and J. Franke, "Reducing the energy consumption of industrial robots in manufacturing systems," International Journal of Advanced Manufacturing Technology, vol. 78, no. 5–8, pp. 1315–1328, 2015.
[9] P. Ferreira, A. Crisostomo, and A. Coimbra, "Energy-efficient trajectory planning for industrial robot manipulators," Industrial Robot: An International Journal, vol. 41, no. 5, pp. 425–433, 2014.
[10] M. Pellicciari, G. Berselli, F. Leali, and A. Vergnano, "A method for reducing the energy consumption of industrial robots in manufacturing systems," Procedia CIRP, vol. 7, pp. 418–423, 2013.
[11] J. Lee, B. Bagheri, and H.-A. Kao, "A cyber-physical systems architecture for Industry 4.0-based manufacturing systems," Manufacturing Letters, vol. 3, pp. 18–23, 2015.
[12] K. Erkorkmaz and Y. Altintas, "High speed CNC system design. Part I: Jerk limited trajectory generation and quintic spline interpolation," International Journal of Machine Tools and Manufacture, vol. 41, no. 9, pp. 1323–1345, 2001.
[13] S. Chiaverini, B. Siciliano, and O. Egeland, "Review of the damped least-squares inverse kinematics with experiments on an industrial robot manipulator," IEEE Transactions on Control Systems Technology, vol. 2, no. 2, pp. 123–134, 1994.
[14] F. Piltan, N. Sulaiman, M. H. Marhaban, and R. Ramli, "Design artificial robust control of robot manipulator based on fuzzy logic inference," International Journal of Robotics and Automation, vol. 2, no. 3, pp. 96–107, 2011.
[15] E. F. Camacho and C. Bordons, Model Predictive Control, 2nd ed. London, U.K.: Springer, 2007.