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A Review of Multi-Degree of Freedom Robot Arm Research

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ABSTRACT

A Robotic Arm is a programmable mechanical device designed to mimic the movement and functionality of a human arm. It consists of interconnected segments joined by joints, enabling precise and versatile motion, often controlled by algorithms and software. Equipped with an end effector, such as a gripper or tool, it can perform a variety of tasks across different fields. Robotic arms operate with degrees of freedom (DoF), which determine their range of motion and complexity. They move through rotational or translational joints powered by actuators and are guided by sensors and microcontrollers for precision and adaptability. This review paper explores the advancements in robotic arms' design, with a focus on lightweight structures and modular components that enhance overall performance, flexibility, and efficiency. A thorough analysis of the fundamentals of kinematics, such as forward and inverse kinematics, reveals how important they are for facilitating accurate movement control. The application of sophisticated control systems that maximize the performance, dependability, and versatility of robotic arms is also covered in the study. The range of uses for robotic arms has greatly increased due to these technical advancements, making them essential in a variety of industries, including manufacturing, healthcare, logistics, and many more.

1. Introduction

The advancements in robotic arms have been pivotal in enhancing automation and efficiency across various industries, particularly in manufacturing and automation. The literature on this subject reveals a trajectory of developments focused on mechanical design, motor sizing and selection, kinematics, control schemes, and practical applications. [1]

Beginning with the foundational work of [2], the integration of multi-body simulation (MBS) into the structural optimization of robotic arms is highlighted. Their study emphasizes the importance of finite element analysis (FEA) in minimizing vibration frequencies and optimizing the mechanical properties of robotic components. By modelling a 2-degrees-of-freedom (2-DOF) robotic arm with an anthropomorphic design, the authors illustrate the iterative process of redesigning based on recalculated motions and torques. This approach not only enhances the structural integrity of the robotic arm but also aligns its functionality with the needs of daily tasks in assistive applications, thus underscoring the significance of kinematics in robotic design.

Following this, [3] expands on the theme of automation in robotic manipulators, addressing the critical need for collision-free path control in high-performance industrial applications. The article discusses the optimization of manipulator structures to prevent collisions while achieving desired poses, which is essential for maintaining operational efficiency in automated environments. Kivelä's insights into the kinematic synthesis for optimizing manipulator dimensions reveal a gap in the existing literature regarding industrially relevant methods for intelligent control of robotic systems. This highlights the growing intersection between academic research and industrial application, as industries increasingly seek automated solutions that enhance productivity and safety.

[4] further the discourse by exploring the advancements in control schemes for n-link revolute manipulators, particularly in the context of landmark navigation. Their work builds upon earlier research, emphasizing the evolution of robotic arms with additional links and the consequent complexity in control strategies. The authors reference a series of studies that have contributed to the stability and motion planning of robotic systems, showcasing the ongoing development of decentralized continuous controls. This body of work illustrates the dynamic nature of robotic arm control and the necessity for sophisticated algorithms to manage the intricacies of multi-link systems, especially in environments that require obstacle avoidance.

Generally, our academic research mainly explains robotic arm technology that has seen remarkable advancements, driving automation and efficiency in manufacturing and other sectors. However, despite these technological strides, there is a notable gap in the literature regarding the comprehensive integration of multi-body simulation (MBS) and finite element analysis (FEA) for the structural optimization of robotic arms. This review aims to address this gap by focusing on the iterative redesign process that leverages MBS and FEA to enhance mechanical properties and reduce vibration frequencies. Furthermore, the review explores the critical need for collision-free path control in robotic manipulators, which is essential for maintaining high efficiency in industrial applications. By bridging the divide between theoretical research and practical industrial needs, this study underscores the importance of developing intelligent control methods that are both academically robust and industrially applicable.

Overall, the literature demonstrates a clear progression in the design, control, and application of robotic arms, reflecting the increasing sophistication of technology and its alignment with industrial needs. Each article contributes to a deeper understanding of the mechanical and computational challenges faced in the field, setting the stage for further advancements in robotic automation. The methodology for this review paper on Robotic Arm robots was structured to comprehensively analyze the evolution, design, kinematics, and control systems of these robots, with a focus on their advancements and industrial applications. The following outline the methodological framework:

A thorough literature review was conducted to gather information on the inception, development, and current trends in Robot Arm. Key academic databases, including IEEE Xplore, typeset, ScienceDirect, SpringerLink, semanticscholar and Google Scholar, were used to source peer-reviewed journal articles, conference papers, patents, and industry reports. The search was focused on publications from 2004 to the present, ensuring coverage of both historical milestones and contemporary advancements.

2. Design

2.1. History of the Robotic Arm

Gasparetto and Scalera (2019) present an insightful exploration into the dawn of industrial robotics, categorizing their evolution into four generations. The first generation, spanning from 1950 to 1967, marked the infancy of robotic technology, where robots were essentially programmable machines with limited capabilities. These early robots could not control the method of task execution nor interact with their external environment. Equipped with basic, low-tech hardware, they lacked sophisticated components like servo-controllers. Instead, they relied on pneumatic actuators and simple "logic gates," which were mechanical systems of cams and relays activating pneumatic or solenoid valves. Their tasks were rudimentary, such as material handling and loading or unloading, and they were often noisy due to collisions with mechanical stops designed to limit arm movement.

Although the journey of industrial robotics formally began in the 1950s, its roots stretch back further. In 1938, Pollard and Roselund developed a programmable paint-sprayer, while Goertz introduced a tele-operated manipulator in 1949. However, the true turning point came with George Devol's groundbreaking invention in 1954: the "Programmable Article Transfer" (Figure 1). This invention laid the foundation for the first "true" industrial robot. To bring his vision to life, Devol partnered with Joseph Engelberger, an engineer with a background in the aerospace industry. Together, they founded Unimation and, in 1961, created the first industrial robot, Unimate. This hydraulically actuated robot was installed at General Motors' Trenton factory, where it performed die-casting operations. While its programming was rigid and complex, limiting it to single tasks, it symbolized a revolutionary step in automation.

Inspired by the success of Unimate, a wave of innovation and entrepreneurship followed. Companies like Ford and General Motors recognized the potential of automation and began integrating robots into their production lines. This surge in demand gave rise to new robotic manufacturers. One notable example was AMF Corporation, which developed the Versatran robot in 1962 (Figure 2). Known for its versatility, Versatran became popular in Ford's production facilities in Canton, Ohio. [5]

Fig. 1. Joseph Engelberger and George Devol (left); the Unimate robot (right) [5].

Building on this momentum, Versatran made history in 1967 as the first robot installed in a Japanese production site, heralding a new era for industrial robotics in the region. By 1969, Japan's involvement deepened when Unimation licensed Kawasaki Heavy Industries to produce robots for the Japanese and Asian markets. This collaboration led to the development of the Kawasaki-Unimate 2000, the first industrial robot built in Japan. This milestone not only solidified Japan's role as a key player in robotics but also set the stage for its eventual dominance in the industry.

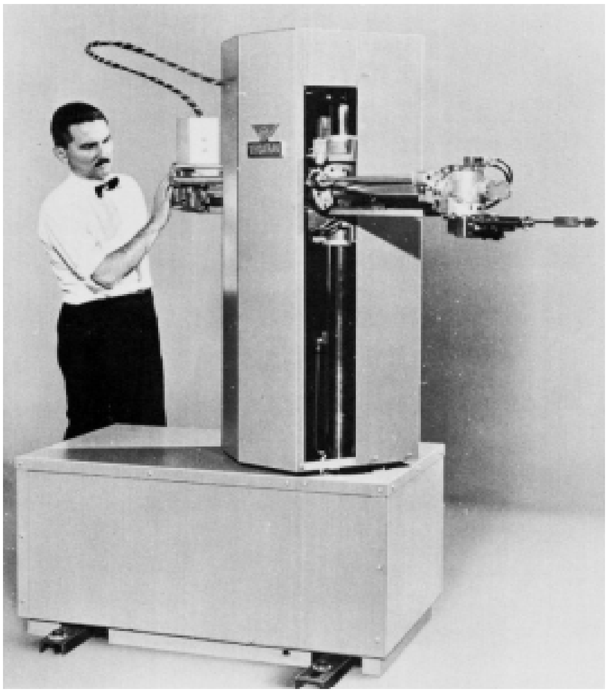

Fig. 2. The Versatran robot [5].

Ultimately, the first generation of industrial robots laid the groundwork for modern automation. From the innovative genius of George Devol and Joseph Engelberger to the rise of robotic manufacturing companies, these early advancements shaped the future of industrial processes. Though limited in functionality, the legacy of these pioneers continues to influence the robotics industry today. [5]

The second generation of industrial robots, which emerged between 1968 and 1977, marked an important step forward in robotics technology. Unlike their predecessors, these robots incorporated servo-controllers, allowing them to perform both point-to-point motions and continuous paths. Although they exhibited only elementary adaptive behavior and limited recognition of their external environment, they represented a significant leap in complexity. Their control systems relied on microprocessors or Programmable Logic Controllers (PLCs), and they could be programmed by operators using a teach box. However, their versatility was limited, as each robot was designed for a specific task, making it difficult to adapt them for other uses without substantial reprogramming and controller modifications. Diagnostics were rudimentary, providing basic failure reports through indicator lights but offering no details about the causes, which left operators to identify the issues manually.

As technology advanced further, the shift from hydraulic to electric actuators began in the 1970s, driven by the maturation of electronic components. Microprocessors and other cost-effective devices enabled manufacturers to implement more powerful and efficient control systems. This shift aligned with the economic and geopolitical landscape of the time. The oil crisis following the Kippur War in 1973 spurred companies to seek more efficient production methods, and electrically driven robots became a logical solution. The adoption of these robots grew rapidly, with installations increasing by over 30% annually in the late 1970s. This trend reflected a broader push toward automation and cost reduction in industrial processes.

Contributing to these advancements was Victor Scheinman, a mechanical engineering student at Stanford University, who in 1969 developed the Stanford Arm (Figure 3), the first prototype of an electrically actuated robot powered by six DC motors and controlled by a PDP-6 microprocessor. Featuring five revolute and one prismatic joint, the Stanford Arm offered six degrees of freedom and was equipped with sensors to measure joint position and velocity. Its innovative design allowed for precise trajectory execution through closed-form inverse kinematics solutions.

In 1973, Scheinman further refined his design, creating the Vicarm, a smaller, lighter robot suitable for tasks like part assembly. Its success caught the attention of Unimation, which acquired the company and used its know-how to produce the PUMA robot in 1978. The PUMA (Programmable Universal Machine for Assembly) became an iconic anthropomorphic robot, its kinematics serving as a reference in robotics education for decades (Figure 4).

While Scheinman's work was groundbreaking, other companies were also advancing robotics technology during this period. In 1973, KUKA introduced the Famulus robot, Latin for "servant," while Cincinnati Milacron developed the T3 robot in 1974. Known as "The Tomorrow Tool," T3 was the first commercially available minicomputer-controlled robot and found widespread use in automotive plants, particularly in Volvo's Swedish facilities (Figure 5). That same year, ASEA (now ABB) launched the IRB series, starting with the IRB-6, a robot renowned for its smooth movement and ability to handle complex tasks like machining and arc-welding. With its vibrant orange color, the IRB-6 became a hallmark of industrial robotics, remaining in production for over two decades (Figure 6).

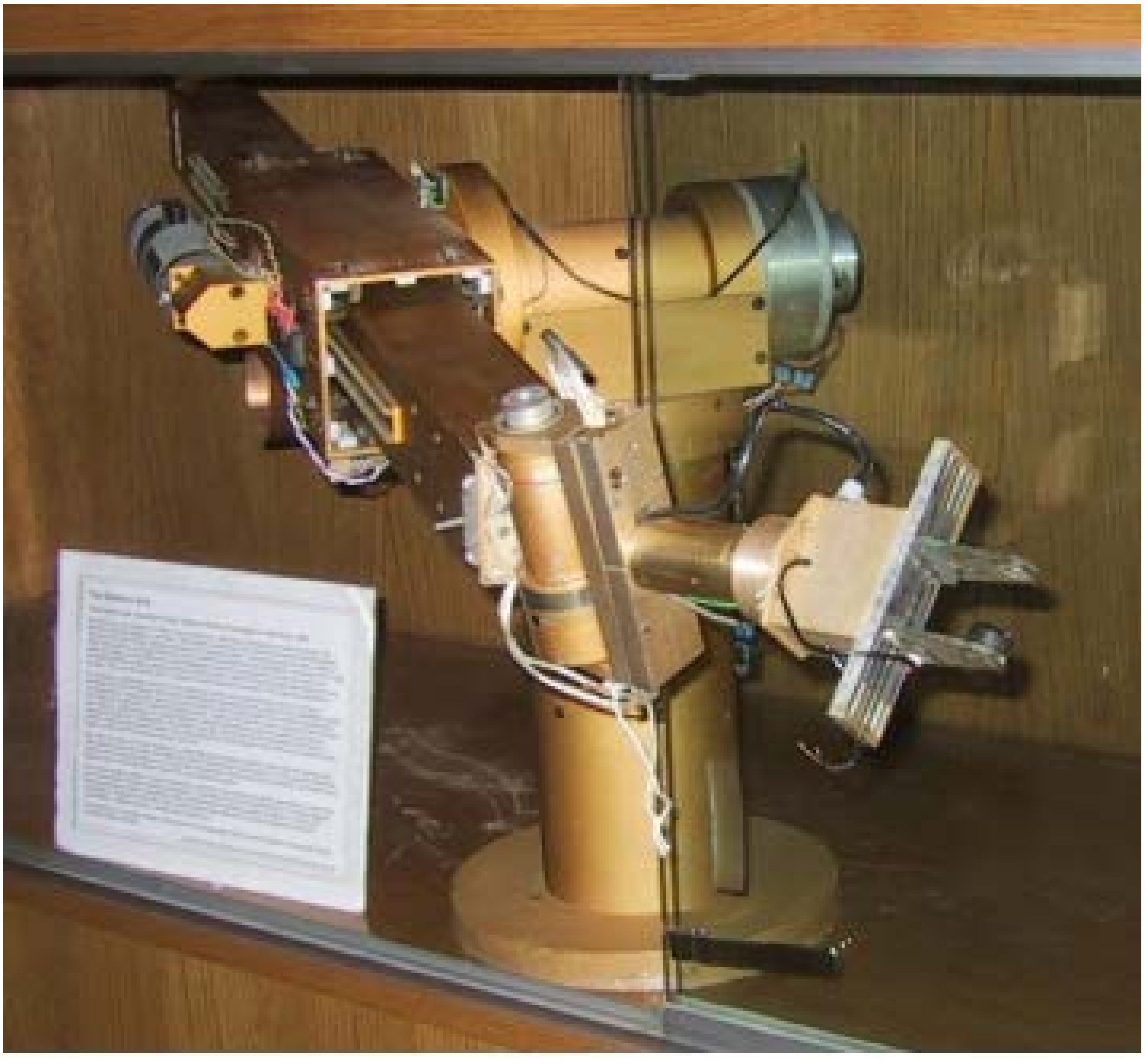

Fig. 3. The Stanford Arm [5].

Fig. 4. The PUMA robot [5].

Fig. 5. The Cincinnati Milacron T3 robot [5].

Fig. 6. The “legendary” ABB IRB robot [5].

In parallel, Japanese companies also contributed to the evolution of second-generation robots. In 1974, Hitachi introduced the HI-T-HAND Expert, notable for its precision in inserting mechanical parts with a clearance of just 10 micrometers. Equipped with a force feedback control system and a flexible wrist mechanism, it demonstrated the potential for enhanced accuracy and adaptability in robotic systems. These advancements from various innovators collectively shaped the second generation of industrial robots, setting the stage for even greater developments in the years to come. [5]

Hiroshi Makino recounts the development of the SCARA robot, or Selective Compliance Assembly Robot Arm, an innovative industrial robot designed for assembly tasks. Invented in 1978, the SCARA stands out for its selective compliance, allowing controlled flexibility in specific directions, which was essential for solving challenges like the "peg-in-hole problem". The project was funded through the SCARA research group, which Makino organized, and by October 1978, the first prototype (Figure 7) was built. Improvements followed with Prototype II (Figure 8) in 1980, incorporating advanced DC motors to enhance precision and resolve vibration issues. [6]

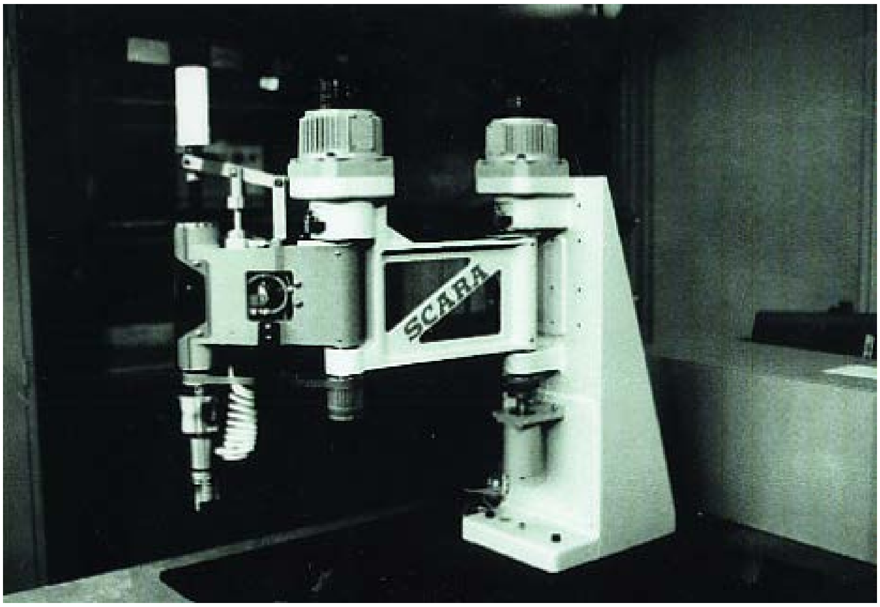

Fig. 7. The first prototype of the SCARA [6].

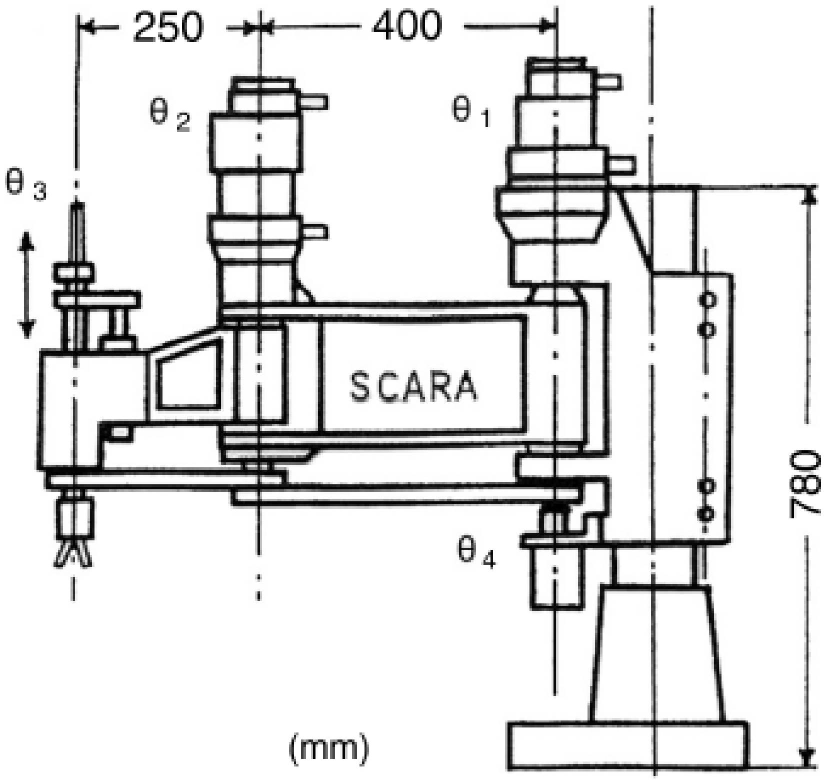

Fig. 8. Configuration and dimensions of SCARA Prototype II [6].

By 1981, SCARA robots were commercially available, with models like Sankyo's SKILAM (Figure 9) showcased at the International Robot Show in Japan. Pioneer Co. quickly adopted the SCARA for industrial use, employing it to assemble audio boards. Its success contributed to the global growth of industrial robotics, with SCARA becoming a key player in Japan's leadership in the field. Recognized for its impact, the SCARA was inducted into the Robot Hall of Fame in 2006, cementing its legacy as a revolutionary innovation in industrial automation.

Fig. 9. Sankyo's SKILAM [6].

Morrell et al. delved into the fascinating history and evolution of robotic surgery, tracing its transformative journey from concept to reality. The paper begins by recounting the origins of robotics, a term coined in 1921 from the Czech word "robota," meaning labor. Over the past 35 years, robotic systems have become a cornerstone of modern surgery, particularly in minimally invasive procedures, thanks to their ability to enhance visualization, dexterity, and precision. The authors aim to present the key milestones and future prospects of robotic surgery, which has redefined standards of care in the medical field. [7]

Morrell et al. highlight early innovations, such as the PUMA 200 robot, first used in 1985 for neurosurgical biopsies, marking the debut of robotics in human surgery. This was followed by the development of the Robotic Surgical System in 1992, which revolutionized orthopedic surgery by allowing precise, patient-specific hip replacements. These systems paved the way for telepresence-based robotics, exemplified by AESOP, a voice-controlled robotic arm introduced in the 1990s. ZEUS, another pioneering platform, brought the master-slave concept to life, enabling surgeons to remotely control robotic arms during procedures. A landmark moment occurred in 2001 with Operation Lindberg, where robotic telesurgery was successfully performed across the Atlantic using the ZEUS system, showcasing the potential of remote surgical interventions.

The authors focus extensively on the evolution of the da Vinci Surgical System, the most widely used platform in robotic surgery today. Developed by Intuitive Surgical, its first generation, Lenny, and its successor, Mona, laid the groundwork for the FDA-approved da Vinci system in 2000. Subsequent iterations, including the da Vinci S (Figure 10), Si (Figure 11), and Xi (Figures 12), introduced groundbreaking features such as 3D-HD imaging, enhanced ergonomic controls, and multi-arm capabilities. These advancements allowed for greater precision, reduced surgeon fatigue, and better patient outcomes, cementing da Vinci's dominance in the field.

Fig. 10. Robot da Vinci S model released in 2006 [7].

Fig. 11. Third generation model of da Vinci: Si model [7].

Morrell et al. also explores future developments in robotic surgery, emphasizing the potential of single-port systems, artificial intelligence integration, and emerging competitors like Versius and Senhance platforms. These systems aim to challenge da Vinci's hegemony by offering innovative features and addressing cost concerns. Despite challenges like high costs and longer operative times, the authors emphasize the growing accessibility and efficiency of robotic-assisted surgery, which continues to push the boundaries of what is possible in modern medicine. [7]

Fig. 12. Intuitive Surgical fourth generation robot, da Vinci Xi System [7].

2.2. Light Weight Robotic Arms

Svemir Popić and Branko Miloradović introduce the innovative concept of lightweight robot arms, which differ significantly from traditional industrial robots. These robots are designed for flexibility and precision in unstructured environments, often working closely with humans. Unlike conventional robots, which focus on repetitive tasks and require heavy components for rigidity, lightweight arms prioritize a low self-weight-to-payload ratio, making them efficient and adaptable. With speeds of up to 6 m/s, they mimic human-like movements and adapt to their surroundings. Table I highlights the differences between these new-generation robots and traditional ones.

Popić and Miloradović explain that lightweight robot arms incorporate advanced materials like carbon fiber, glass composites, and lightweight alloys such as aluminum and titanium. These materials reduce mass and inertia, leading to safer and more efficient operation. Figures such as Fig. 13 and Fig. 14 showcase examples like the Barrett WAM arm and the DLR-KUKA lightweight robot, emphasizing their modularity and advanced design. These robots, with their reduced weight and power, provide safer interactions with humans. [8]

Fig. 13. Barrett hand with Barrett wrist [8].

Fig. 14. DLR – KUKA Lightweight robot [8].

The authors highlight key technological advancements, such as force and torque sensors like the Barrett 6-axis sensor. These sensors allow the robots to sense and adapt to their environment, making them ideal for applications like rehabilitation, where precise control is essential. Additionally, the modularity of systems, enables robots to be tailored for specific tasks, broadening their applications in medicine and industrial automation.

Popić and Miloradović describe innovative drive systems, which use steel cables to transmit torque smoothly and quietly. This approach eliminates bulky gears, reducing weight while improving performance.

Finally, lightweight robot arms have proven their value in real-world applications. For example, the Barrett WAM arm in rehabilitation, where it assists patients by guiding them through exercises with appropriate force. This adaptability and precision make lightweight robots indispensable for tasks requiring safety and reliability. [8]

2.3. Mechanical Design

The mechanical system of robotic arms discusses the physical form of the hand and arm as well as its components. It specifies the mechanical design, including the type of materials, sensors like position encoders and actuators like electric motors. The mechanical design is defined by the basics of the arm and hand, for example the types of objects that can be gripped and the manipulations that may be carried out with a grasped object. Many factors, including the manipulator's geometry, the dynamics at play, the linkage system's structural features, and the actuator's characteristics, also affect the design of the robotic arm. [9], [10]

The human arm and the robotic arm are similar as illustrated in fig.15, The shoulder of the robot is the immovable component to which all other components are linked. The links are made to be light components in order to minimize their weight, which is essential for lowering the power usage when they are operating. As the joints are simple revolute, the level of redundancy in robotic manipulators determines their dexterity and manipulability. The reason why serial robotic arms are so common in industrial settings is its uncomplicated designs. Additionally, joint fault tolerance is a feature of serial robotic manipulators. [10]

The mechanical movement of any robotic arm can be produced by hydraulic or pneumatic cylinders but in general it is produced by electric motors. DC motors with integrated gearing and feedback control loop circuits are known as servos. Robot, RC plane, and RC boat builders are big fans of servos. The majority of servo motors have a 90–180-degree rotational range. There are some that revolve 360 degrees or more. [9] Although servos cannot rotate continuously, which means they cannot be used to drive wheels until they are changed, their precise positioning makes them perfect for a variety of applications, such as sensor scanners, rack and pinion steering, and robot arms and legs. The velocity and angle control loops are relatively simple to design because servos are completely self-contained, and prices are still fairly.

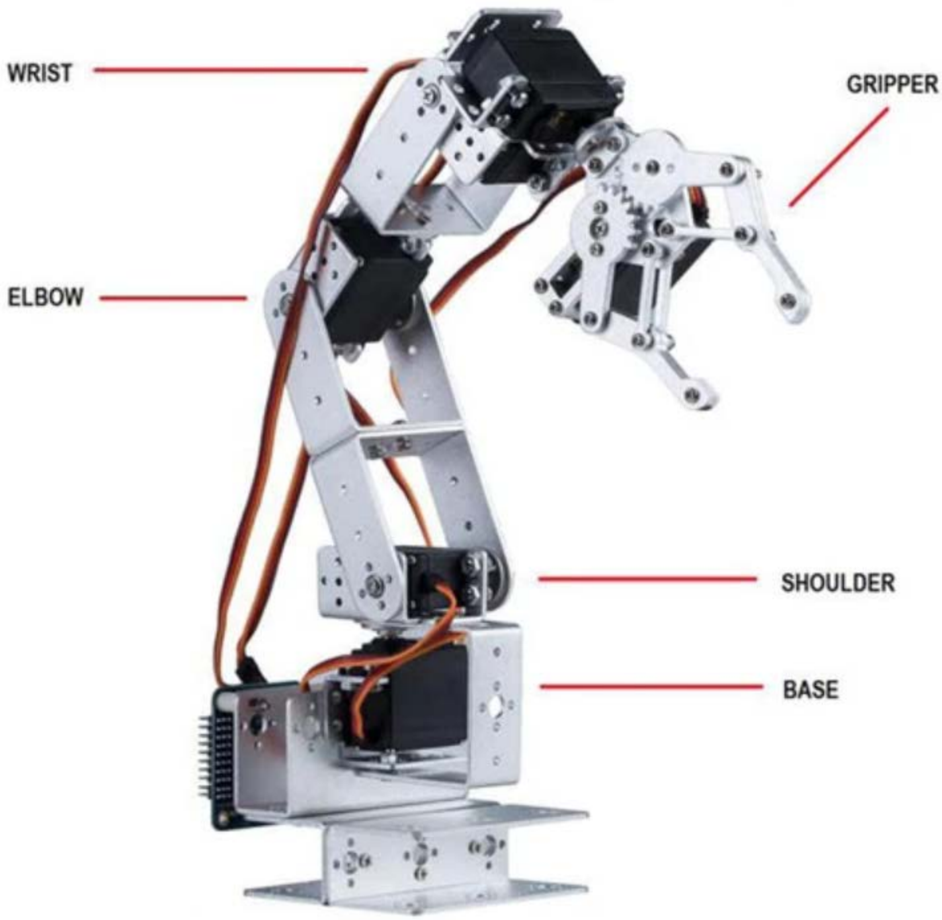

Fig. 15. Model of Robotic Arm [11].

The level of redundancy in robotic manipulators determines their dexterity and manipulability. The reason why serial robotic arms are so common in industrial settings is its uncomplicated designs. Additionally, joint fault tolerance is a feature of serial robotic manipulators.

For as long as possible, the design process for robotic arms should be automated. or at the very least, lessen the requirement for developer assistance, so third-party resources are used in addition to established software tools during the design process. The most crucial is the SolidWorks CAD system, which allows for the creation of 3D models of the devices that have been designed as well as the execution of kinematic, dynamic, and strength assessments, among other duties.

Currently, robotic arm designs are exclusively regarded as item manipulation jobs. The design process is illustrated as a block diagram in Figure 16. [12]

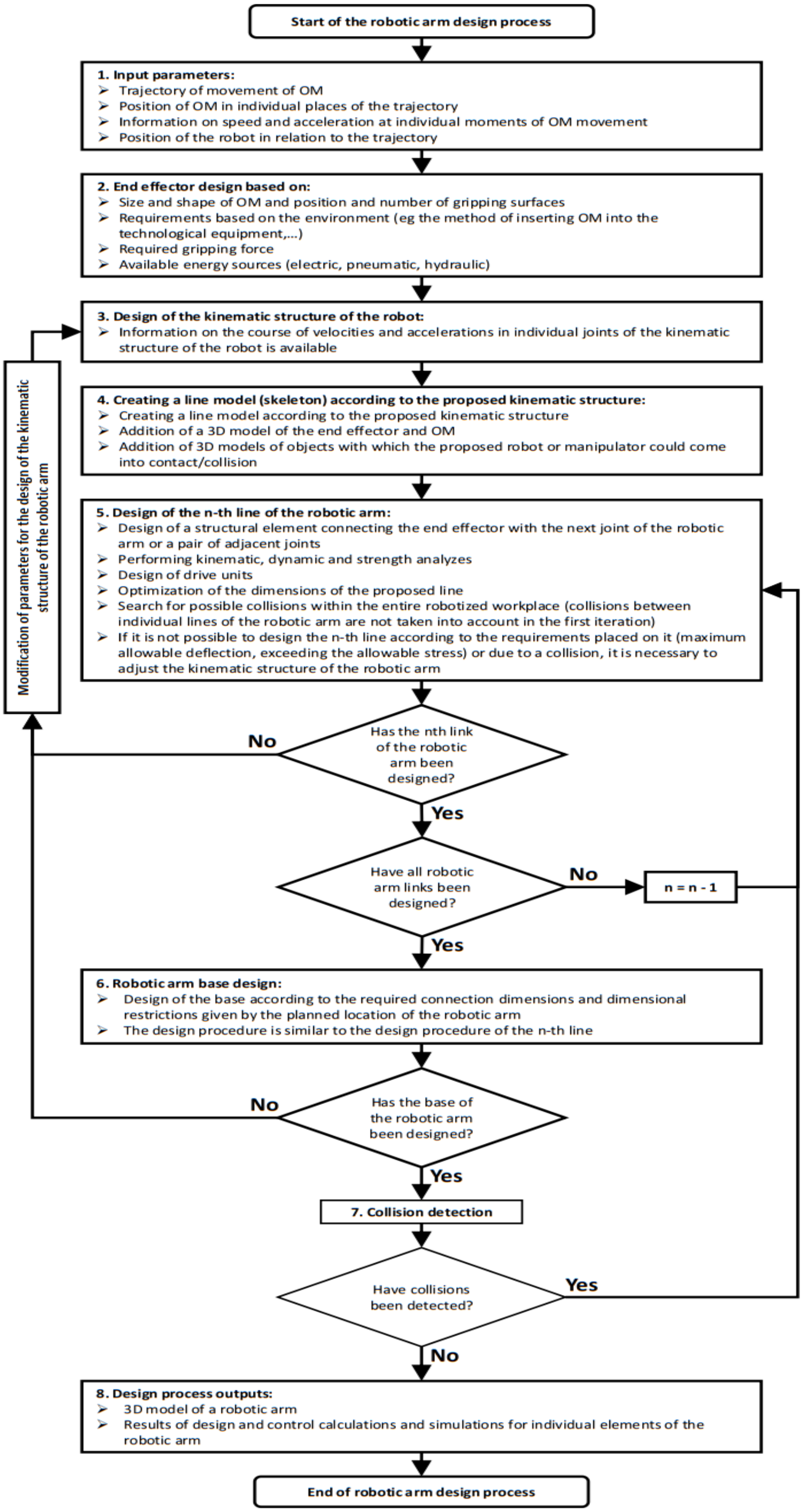

Fig. 16. Block diagram of the robotic arm design process [12].

The design of each component in a robotic arm is an iterative process. Modifying one part can influence the design of connected components. Fig. 16. outlines the design process for a single robotic arm line and its associated drive units. Throughout this procedure, drive units are iteratively constructed, and kinematic, dynamic, and structural evaluations are conducted. Initially, the design focuses on avoiding collisions between the arm and workplace elements. Subsequent iterations consider potential collisions within the arm's structure itself. The goal is to optimize the design for factors like weight, dimensions, and functionality.

The design process is divided based on link length. For shorter links (less than four times the previous component's diameter), a single-piece design is feasible. However, for longer links, a three-piece design (consoles and connecting profile) is necessary. This modular approach ensures structural integrity and flexibility in the design.

2.4. Limits of Performance Under Safety Constraints:

Defining measurable parameters for safety and performance is critical for discussing combined actuation strategies, though no universal formula can fully address such complexity. A key focus is the risk of unanticipated accidents between a robot manipulator and a human operator, where impacts can occur anywhere on the manipulator or the operator’s body during trajectory execution. Studies on collision severity, recently applied to robotics, are well-documented in biomechanics, particularly in sports and auto accidents [13]

2.5. Understanding the Process

The optimization of structural elements in robotic arm design is a critical step in ensuring the overall performance and efficiency of the system. By systematically exploring the design space and evaluating various dimensional combinations, engineers can identify the optimal design that meets specific performance criteria.

2.6. Key Steps

2.6.1. 3D Model Creation

- A 3D CAD model of the structural element is created using software like SolidWorks.
- Key dimensions, such as length, width, and thickness, are identified as design variables.
- Boundary conditions and loading conditions are defined to simulate real-world scenarios.

2.6.2. Design Space Definition

- Ranges for each design variable are established, defining the feasible design space.
- These ranges can be based on manufacturing constraints, material properties, or performance requirements.

2.6.3. Finite Element Analysis (FEA)

- The 3D model is subjected to FEA to determine its structural response under the specified loading conditions.
- Key parameters, such as stress, strain, and displacement, are calculated and compared to design criteria.

2.6.4. Optimization Algorithm

- A suitable optimization algorithm (e.g., genetic algorithms, gradient-based optimization) is employed to explore the design space efficiently.
- The algorithm iteratively modifies the design variables to minimize or maximize a specific objective function (e.g., weight, stress, deflection).

2.6.5. Design Evaluation and Update

- The optimized design is evaluated based on the specified criteria.
- If the design meets the requirements, the process is complete.
- If not, the optimization process is repeated with adjusted design parameters.

2.7. Challenges and Considerations

- Computational Cost: FEA simulations can be computationally expensive, especially for complex models and large design spaces.
- Design Constraints: Manufacturing limitations, material properties, and assembly constraints must be considered.
- Multi-Objective Optimization: Often, multiple objectives (e.g., weight minimization, stiffness maximization) need to be balanced.
- Sensitivity Analysis: Understanding how changes in design parameters affect the performance of the structure is crucial.

2.8. Advanced Techniques

- Topology Optimization: This method can determine the ideal material allocation within a designated design space to meet particular performance objectives.
- Shape Optimization: This entails altering the configuration of the structure to enhance its efficacy.
- Size Optimization: This focuses on optimizing the dimensions of structural elements.

By effectively addressing these challenges and leveraging advanced optimization techniques, engineers can design lightweight, strong, and efficient robotic arm structures.

3. Kinematics of Robotic Arms

In robotics, kinematics plays a major role in understanding and controlling the movement of robotic systems in general, and with a robot arm specifically; kinematics helps us understand how the movements of each joint in the arm affect the position and orientation of the hand (or the tool it's holding). There are two key aspects of kinematics in robotics which are forward kinematics and inverse kinematics, and we will delve deeply into each aspect.

3.1. Forward Kinematics

It’s concerned with determining the position and orientation of the end-effector (the tool or object held by the arm) given the angles of the joints. This involves understanding how the movements of each joint contribute to the overall position of the end-effector.

The predominant convention for determining frames of reference in robotic applications is the Denavit-Hartenberg (DH) convention. By applying a series of transformations (rotations and translations) based on the DH parameters, the forward kinematic equations can be derived. [14]

The general form of the Denavit-Hartenberg (DH) transformation matrix is:

$$T_i^{i+1} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & \alpha_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & \alpha_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where the four quantities ai, di, αi (alpha) and θi (theta) are parameters related to link i and joint i. The four parameters are generally given the names link length, link offset, link twist and joint angle respectively. [15]

The Top Left 3x3 Submatrix: Represents the rotation part, Top Right 3x1 Column: Represents the translation part, Bottom Row: Is always [0 0 0 1] for 4x4 homogeneous transformation matrices.

The Key idea of this matrix describes how to transform the coordinate frame of one link to the coordinate frame of the next link in a robotic arm. By multiplying a series of these matrices together, one can ascertain the comprehensive position and orientation of the robot's end-effector. In practice, the coordinate frames for each link should be carefully defined and determine the appropriate DH parameters for each specific robot arm.

3.2. Inverse Kinematics

Calculating the joint angles required to achieve a desired position and orientation of the end-effector. This is often more complex and challenging than forward kinematics.

3.2.1. Why is it Challenging:

- Non-linearity: The relationship between joint angles and the end-effector position is not always
- straightforward.
- Singularities: There might be certain positions where the robot loses some degrees of freedom, making it
- difficult to reach certain targets.
- Multiple Solutions: Often, there are multiple ways to position the robot arm to reach the same target.

For example, consider a three joint simple robotic arm with an end effector, any position can be reached inside of its working envelope with any orientation. In both figures the dashed lines represent a second possible configuration in which the same end-effector position and orientation are achieved.

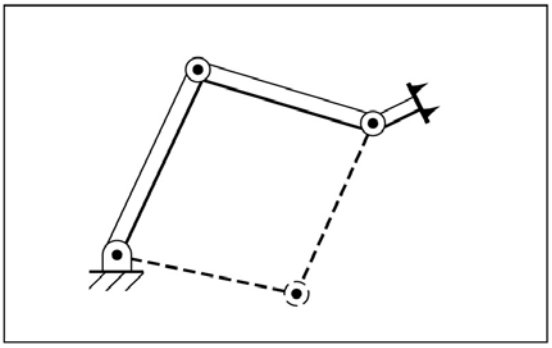

Fig 17. Three-link manipulator. Dashed lines indicate a second solution [16]

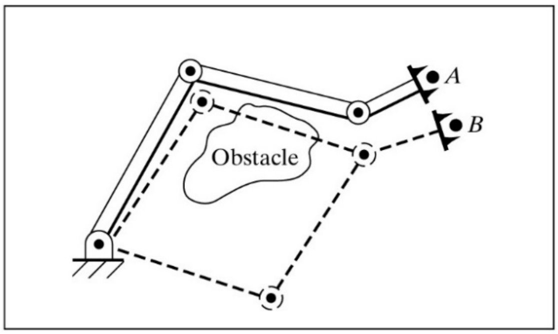

Fig. 18. One of the two possible solutions to reach point B causes a collision [16].

Those multiple solutions can cause extensive problems due to the system's obligation to choose the best route. The criteria for decision-making differ, although a very rational option would be the most proximate solution. For instance, if the manipulator is positioned at point A, as illustrated in Fig.18, and we intend to relocate it to point B, an optimal approach would be to select the solution that minimizes the movement required by each joint. Therefore, in the absence of the obstruction, the top dashed arrangement in Fig.18 would be selected. This implies that the current position of the manipulator may serve as one input parameter for our kinematic inverse process. [16]

For solving the inverse kinematics[17], the total transformation matrix from joint one to joint five can be calculated as follows:

$$T_5^1 = A_1A_2A_3A_4A_4 = \begin{bmatrix} n_x & o_x & a_x & P_x \\ n_y & o_y & a_y & P_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where, n_x n_y n_z, o_x o_y o_z, a_x a_y a_z are rotation parameters around (x, y, z) axis and P_x P_y P_z are the position parameters. as the Inverse Kinematic (IK) problem is required to be solved to get the five joints angles (θ_1, θ_2, θ_3, θ_4 and θ_5) to locate the desired position and orientation. [17]

3.3. Jacobian Matrix

The Jacobian Matrix is a crucial tool that relates the joint velocities of a robotic arm to the linear and angular velocities of its end-effector. The Jacobian computes linear and rotational velocity independently.[18]

linear velocity $\dot{p}$ and the angular velocities ω is the function of joint velocity $\dot{q}$, where J_p and J_o are the linear and angular parts of the Jacobian matrix.

$$v = \dot{p} = J_p(q)\dot{q}$$

$$\omega = J_o(q)\dot{q}$$

$$J(q)\dot{q} = \begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \dot{p} \\ \omega \end{bmatrix}$$

Jacobian 6xn matrix form:

$$J(q) = \begin{bmatrix} J_p(q) \\ J_o(q) \end{bmatrix}$$

where $J_p(q)$ and $J_o(q)$ are 3x1 matrices describing the linear and angular parts of motion respectively.

General form:

$$J(q) = \begin{bmatrix} J_{p1}(q) & \cdots & J_{pn}(q) \\ J_{o1}(q) & \cdots & J_{on}(q) \end{bmatrix}$$

3.4. Computational Complexity and Optimization Methods in Inverse Kinematics

The inverse kinematics (IK) problem for multi-degree-of-freedom (multi-DOF) robotic arms presents significant computational challenges due to its inherently nonlinear and often non-analytic nature. As the number of degrees of freedom increases, the mathematical relationships between joint parameters and the end-effector's position and orientation grow increasingly complex. These challenges are further exacerbated in real-time applications, where high computational efficiency is critical.

3.4.1. Computational Complexity

The nonlinear nature of IK equations means that closed-form solutions are not always feasible. Iterative numerical methods, such as the Jacobian inverse or Levenberg-Marquardt algorithms, are commonly employed but suffer from high computational costs and may fail near singular configurations or in the presence of multiple solutions. For redundant robotic arms, where the system has more degrees of freedom than necessary to achieve a task, the problem becomes under-determined, leading to an infinite number of possible solutions. Selecting the optimal solution requires additional computations, often increasing the complexity of real-time implementations.

3.4.2. Optimization-Based Methods

To address these computational challenges, several optimization-based and learning-enhanced techniques have been proposed:

1. **Metaheuristic Approaches**: Algorithms such as Particle Swarm Optimization (PSO) have been successfully applied to solve IK problems. For example, Collins and Shen demonstrated the effectiveness of PSO in solving high-dimensional IK problems for snake-like robots [19]. These approaches explore the solution space globally, making them robust to local minima but computationally expensive.

2. **Learning-Based Enhancements**: Recent advancements in machine learning have introduced hybrid methods, where neural networks provide initial guesses for joint configurations, significantly reducing the computational burden of traditional iterative solvers. Tenhumberg et al. presented a framework combining neural network predictions with Jacobian-based optimization to achieve collision-free IK solutions for humanoid robots in under 10 milliseconds [20].

3. **Gradient-Based Refinements**: Gradient descent methods are often employed to fine-tune solutions obtained from heuristic or learning-based methods. These approaches use the Jacobian matrix to iteratively improve the joint configurations while satisfying positional and orientation constraints.

4. **Collision Avoidance Optimization**: For applications in cluttered environments, optimization-based methods integrate collision avoidance constraints directly into the IK formulation. Signed Distance Fields (SDFs) are used to model obstacle boundaries, and additional terms in the objective function penalize configurations leading to collisions [21].

3.4.3. Performance and Practicality

The efficiency of these methods varies depending on the application. Learning-based methods excel in real-time scenarios by leveraging pre-trained models to predict solutions rapidly. Meanwhile, optimization techniques offer greater precision and adaptability to complex constraints, albeit at a higher computational cost.

By combining traditional optimization techniques with modern learning-based methods, the IK problem for multi-DOF robots is becoming increasingly solvable in practical settings, paving the way for advancements in robotic manipulation, navigation, and automation.

4. Control

The simplest approach to controlling a robotic arm is using a closed loop PID based control systems [21].
The control system for the 4-DOF robot arm in this study utilizes a PID-based kinematic control strategy, specifically for position control of four stepper motors. The Arduino Mega microcontroller generates control signals, driving the motors through PWM. Feedback from the motor encoders is used to fine-tune motor positions for precise control, ensuring accurate pick-and-place tasks. MATLAB GUI interfaces with the controller for user interaction and real-time system performance evaluation. Shows in Figure 19.

A key feature of the robotic arm’s control system is the integration of a PID (Proportional, Integral, Derivative) controller, which adjusts the motor’s speed and position to minimize error. The PID controller ensures that the motor reaches and maintains the desired position by continuously adjusting the control signals in real-time based on feedback from position sensors [22]. Feedback can be provided by encoders or potentiometers, which monitor the motor's position and send this data back to the Arduino, allowing it to make real-time corrections to its output commands[23].

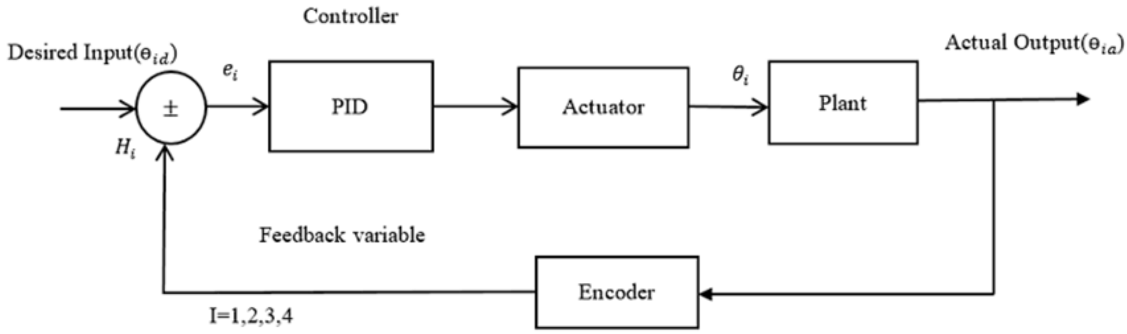

Fig. 19. PID-based control system for the 4-DOF robotic arm [21].

4.1. MATLAB-Based Simulation and Deployment

A simpler approach involves utilizing MATLAB for programming, simulating, and deploying robotic arm control on an Arduino board. Alia et al. [24] describe a comprehensive framework for analysing and simulating the kinematics of robotic arms using Denavit-Hartenberg (D-H) parameters. This framework facilitates trajectory planning, visualizing 3D models, and implementing real-time control strategies

4.1.1. Modeling & Simulation (MATLAB)

- Model the robotic arm using Denavit-Hartenberg parameters for kinematics.
- Derive forward and inverse kinematics equations.
- Calculate the Jacobian matrix for velocity kinematics.
- Implement trajectory planning using MATLAB’s built-in functions and simulate the arm's movement in a 3D environment.

4.1.2. Programming the Arduino

- Set up the Arduino board with motor drivers for controlling the robotic arm's joints.
- Implement inverse kinematics on Arduino to calculate joint angles from desired end-effector positions.
- Use a loop to continuously update joint angles and control the motors based on computed data.
- Use PWM signals or stepper drivers to control motor movements.

4.1.3. Communication Between MATLAB and Arduino

- Use MATLAB's serial interface to send joint angle data to the Arduino board.
- In Arduino code, receive serial data, convert it into motor control commands, and adjust motor positions accordingly.

4.1.4. Deploying to the Arduino

- Test the control system by running the Arduino code and observing the robotic arm's movement.
- Fine-tune the inverse kinematics and adjust parameters for better performance.
- Implement safety checks, such as limit switches, for motor protection.
- Deploy the robotic arm for real-world tasks after ensuring the control system is stable and accurate. [24]

4.2. Motor Control with NEMA 24 and NEMA 34 Stepper Motors:

The NEMA 24 and NEMA 34 stepper motors provide high torque and precision, crucial for controlling the arm's movements with accuracy. These motors are driven by step pulses from the Arduino Mega, with each pulse resulting in precise movement, making them ideal for robotic arms requiring accurate positioning [23]. Stepper motors are also well-suited for applications needing high holding torque, such as industrial robotic arms managing significant loads [24]**.**

NEMA 24 stepper motors typically use drivers like the A4988 or DRV8825, while NEMA 34 motors require more powerful drivers such as the TB6600, capable of handling increased current and voltage requirements [22]. These drivers' interface with the Arduino Mega to convert digital control signals into the necessary power for motor operation while ensuring system protection from overcurrent conditions[25].

5. Applications

5.1 The Growing Role of Robotic Arms Across Industries:

The growing impact of robotic arms on various industries has demonstrated their pivotal role in enhancing automation, precision, and operational efficiency. [26] Robotic arms are transforming sectors such as manufacturing, healthcare, agriculture, and space exploration by automating complex tasks with high precision. Additionally, the integration of artificial intelligence (AI) and machine learning is significantly enhancing the capabilities of robotic arms, allowing them to adapt to changing environments and take on more autonomous roles in diverse applications.

5.2 The Advancements and Applications of Robotic Arms:

Rapid advancements in robotic arm technology have led to their expanding applications across multiple sectors.[27] Robotic arms are increasingly utilized for automating repetitive and precision-dependent tasks, improving efficiency, and minimizing human errors. The integration of artificial intelligence (AI) has further enhanced their flexibility, enabling them to handle more complex operations in dynamic environments. This innovation is transforming industries such as manufacturing, healthcare, and logistics, broadening the scope of robotic automation.

5.3 The Impact of Intelligent Robotic Arms on Industry:

Robotic arms are playing a significant role in enhancing industrial processes, contributing to improved efficiency and precision. [28] These advanced systems are streamlining operations in industries like manufacturing, healthcare, and agriculture by automating complex processes such as assembly, surgery, and harvesting. The integration of advanced technologies, especially artificial intelligence, is essential for enhancing the adaptability and autonomy of robotic arms, allowing them to handle more sophisticated tasks across diverse fields.

5.4 Dual-Arm Robotic Manipulation with Mask R-CNN for Complex Objects:

Advancements in robotic arm technology are increasingly focusing on applications in various industries. Robotic arms, powered by AI and advanced control systems, are being utilized in manufacturing, healthcare, and logistics for tasks requiring high precision and complexity. These systems are becoming more flexible, efficient, and autonomous, capable of handling a wider range of applications, especially in dynamic and unpredictable environments. [29]

5.5 Advancements in Robotic Arms: Enhancing Efficiency and Precision Across Industries:

The integration of robotic arms in industrial settings is significantly enhancing automation and precision. These systems are widely used in sectors like manufacturing and healthcare to optimize operations by performing complex tasks with high accuracy [30]. Advanced control systems and artificial intelligence play a crucial role in enabling robotic arms to adapt to changing environments, making them more capable of handling diverse tasks autonomously and expanding their potential across multiple industries.

5.6 The Role of Robotic Arms in Industrial Automation: Design and Applications:

This paper explores the growing role of robotic arms in industrial applications, especially in settings where manual labor is costly [31]. It references the Robot Institute of America’s definition of robots and emphasizes the versatility of manipulators in industrial, military, and educational fields due to their intelligence and real-time capabilities. Various robot configurations, including Cartesian, cylindrical, polar, and articulated robots, are discussed. The focus is on a four-degree-of-freedom (DOF) robot manipulator with revolute joints for the base, shoulder, elbow, and wrist, designed for flexible and smooth operations in tasks like material handling, welding, assembly, and processing.

6. The Evolution and Future of Robotic Arms:

Jehangir Arshad and his team embarked on a journey to revolutionize assistive technology with their innovative study on controlling robotic arms using Brain-Computer Interface (BCI) and Artificial Intelligence (AI). They envisioned a system that captures brain signals through non-invasive EEG devices, translating thoughts into robotic arm movements to aid physically disabled individuals. Using machine learning techniques, they analyzed EEG signals to classify movements with algorithms like Random Forest, Gradient Boosting, and KNN, achieving a peak accuracy of 76%

with Random Forest. Their prototype integrates Python and Arduino, making it both cost-effective and practical. By optimizing EEG electrode placements and leveraging AI for signal processing, they not only developed a robust system but also opened doors to applications in prosthetics, education, and even autonomous systems, setting a new benchmark in human-machine interaction. [32]

Sander De Witte and his team embarked on an ambitious journey to harness the power of artificial intelligence for robotic collaboration. In their work, they explored how two robotic arms could cooperate to perform complex pick-and-place tasks that no single arm could achieve alone. Using deep reinforcement learning, they trained a hierarchical control system capable of dynamically adapting to changes in the environment, such as shifts in object position or task goals. Their AI-driven approach allowed the robotic arms to coordinate in real-time, optimizing their actions to achieve precise placements and orientations. Through simulation and real-world testing, they discovered that their method not only enhanced efficiency but also revealed how AI can empower multi-robot systems to exceed individual limitations, paving the way for innovative applications in automation and manufacturing. [33]

Dr. Jayashree P. Tamkhade and her team embarked on a mission to revolutionize waste management through artificial intelligence and robotics. Their project leverages deep learning to create an automated garbage segregation system integrated with a robotic arm. Using advanced algorithms like convolutional neural networks (CNNs), the system analyzes images of waste to classify materials such as plastics, metals, and glass with remarkable accuracy. The robotic arm, guided by these classifications, efficiently picks and sorts waste into appropriate bins. This innovation marks a significant leap in the evolution of robotic arms, showcasing their ability to handle complex, real-world tasks with precision and intelligence. Their work not only enhances the efficiency of waste management systems but also points toward a sustainable future, where AI-driven robotics play a pivotal role in promoting environmental conservation and tackling global waste challenges. [34]

7. Conclusion

The advancements in multi-degree-of-freedom robotic arms represent a transformative leap in technology, offering enhanced precision, adaptability, and efficiency across diverse applications. Through innovations in mechanical design, kinematics, and control systems, robotic arms have transcended their initial industrial functions to revolutionize fields such as healthcare, manufacturing, and autonomous systems. The integration of finite element analysis and kinematic modeling has enabled optimized designs with reduced vibration and enhanced structural integrity, while the incorporation of artificial intelligence and machine learning has unlocked new potentials for autonomous decision-making and adaptability. This review underscores the critical role of iterative processes in advancing robotic arm technology, bridging theoretical research and practical applications. From lightweight structures and modular designs to collision-free path planning and intelligent control algorithms, robotic arms continue to evolve, meeting the demands of increasingly complex tasks. The interdisciplinary efforts of engineers, researchers, and technologists pave the way for a future where robotic systems seamlessly integrate into human-centric environments, enhancing productivity, safety, and innovation. As the boundaries of automation expand, the convergence of cutting-edge technologies positions robotic arms as a cornerstone of Industry 4.0 and beyond. By addressing current challenges and leveraging emerging opportunities, the field stands poised to redefine the limits of what is achievable in robotic manipulation and human-machine collaboration.

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