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TOPICAL REVIEW

In-Depth Review of Advanced Control Strategies and Cutting-Edge Trends in Robot Manipulators: Analyzing the Latest Developments and Techniques

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ABSTRACT It is undeniable that the development of robot manipulators has gained significant attention due to its numerous applications in various sectors. In order to address and resolve several issues for robotic manipulators, this paper provides a review of recent control approaches that have been conducted. In the beginning, a succinct comprehensive introduction of the pertinent terminology, configurations, components, advantages/disadvantages, and applications is given. A state-of-the-art review of the various control strategies for robotic manipulator systems is then presented, along with potential solutions when the systems are faced with various obstacles and impediments. An analytical study is discussed showing percentages of the papers discussed in this study in terms of the different control strategies, link types, models, applications, and degrees of freedom of robotic manipulators. For academic, research, medical, and industrial uses, some off-the-shelf developments in robotic manipulators are also presented.

INDEX TERMS Arm manipulators, rigid-link manipulators, flexible-link manipulators, rigid-flexible manipulators, multi-link manipulators, trajectory tracking, control systems, robotic control, industrial manipulators, medical manipulators.

I. INTRODUCTION

During recent decades, manipulators have increasingly drawn interest from research and industrial sectors to improve their automation, efficiency, and employment [1]. They have so far been extensively used in the manufacturing, healthcare, freight handling, nuclear domain, and space exploration sectors [2], [3], [4]. They have steadily taken the place of humans in a variety of environments to perform duplicative and monotonous tasks [5]. Generally, the manipulators can be divided into three categories: rigid manipulator (RM), flexible manipulator (FM), and rigid-flexible manipulator (RFM). **Table 1** illustrates the advantages and limitations of each category, while **Figure 1** illustrates the differences graphically.

In general, A robotic manipulator is a device that is electronically operated and has a combination of mechanical, electrical, and electronic components. It can be fully autonomous or controlled by an operator. A manipulator mimics a human arm with a variable range of motion and dexterity. The size, purpose, and degrees of freedom (DOF) of robotic manipulators vary, allowing for a variety of configurations that are suitable for various tasks. The end-effector (tip) can be replaceable, providing a variety of options to satisfy

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TABLE 1. **The advantages and limitations of rigid, flexible, and rigid-flexible manipulators [1], [5], [6], [7].**

	Rigid Manipulator	Flexible Manipulator	Rigid-Flexible Manipulator
Advantages	• Stronger load capacity • High rigidity • Minimum vibration	• Light weight • Low energy consumption • Economical • Portability • High maneuverability • Smaller actuators	• Light weight • High flexibility • Capacity to carry payloads • High operational speed • High transportability
Limitations	• Uncertainties • Deformation under large loading and high speed • Larger actuator • Costly	• Control complexity • Uncertainties • Multi-input-multi-output (MIMO) nonlinear system • Vibrations due to low natural frequencies resulting from the low stiffness mechanisms • Spillover problem	• Coupling effect • Vibrations • Difficulty in controlling the tip position • High nonlinearity • Actuator saturation
Usages	• Space robots • Flapping wing robots	• Ground robots • Deep sea robots • Surgery and rescue operations • Flexible wings	• Manipulator-needle system "needle insertion"

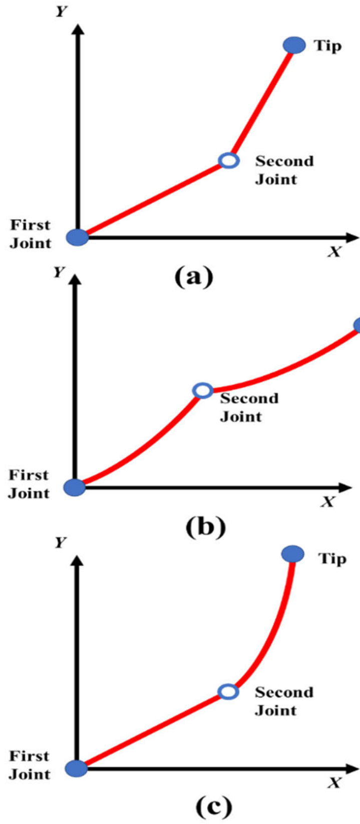

FIGURE 1. **(a) Rigid (b) flexible, and (c) rigid-flexible manipulators.**

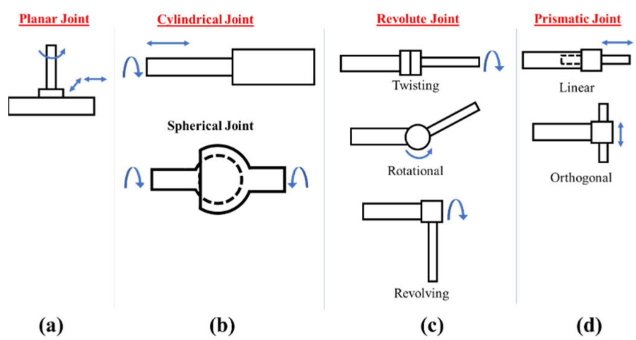

FIGURE 2. **Types of joints (a) Planar (b) Cylindrical, (c) Revolute, and (d) Prismatic.**

certain task needs and varying in form and functionality [8], [9], [10].

A robotic manipulator is made up of a series of joints (connections) that are analogous to a shoulder, elbow, or wrist to connect various links that resemble an upper arm or fore-arm to permit an end-effector to be moved to a particular status or direction. As shown in **Figure 2**, the joints of a manipulator are typically revolute (rotational, revolving, and twisting) joints that rotate around one axis, prismatic (linear or orthogonal) joints that translate about one axis, cylindrical joints that rotate and translate about one axis, spherical joints that rotate about three axes, or planer joints that rotate about one axis and translate around two axes.

A manipulator is referred to as a direct-drive manipulator if each joint is driven directly by an actuator without the need for a speed reducer, and a conventional serial manipulator is if each moving link is driven by a single actuator installed on the link before it via a gear reduction unit. An end-effector typically comes in several forms: a gripper (such as an electric, pneumatic, magnetic, mechanical, or suction cup gripper), a process tool (like robot welding, polishing, screwing, dispensing, or painting), a sensor (such as infrared sensors, 2D and 3D cameras, laser scanners, or ultrasonic sensors). Thus, this is the main reason that these robotic manipulators have been utilized for several purposes such as finishing specific surfaces, gripping objects, picking and dropping the units from one place to another, assembly assignments in an industry, testing and inspecting objects [8], [9].

A variety of manipulators are used in accordance with requirements and needs. They can be classified according to a variety of criteria such as DOF, kinematic structure, drive technology, workspace geometry, and motion characteristics as depicted in **Table 2** [8], [9].

Manipulators differ from a modeling perspective based on whether links are flexible, rigid, or a combination of both. Although rigid-link manipulators are easier to model,

TABLE 2. Classifications and types of robot manipulators [8], [9].

Criteria	Classification scheme
Degrees of Freedom	• General purpose robot – 6 DOF • Redundant robot – more than 6 DOF • Deficient robot – less than 6 DOF
Kinematic Mechanism	• Serial Robots or Open-loop robotic manipulators have links that form in an open chain. • Parallel robots or Closed-loop robotic manipulators have links that form in a close chain. • Hybrid Robots or Hybrid robotic manipulators are the only category that consists of open-loop as well as closed-loop chains.
Drive Technology	• Electric (dc servomotors or stepper motors): clean and relatively easy to control • Hydraulic: for high speed and/or high load-carrying capabilities however one of the disadvantages is the possibility of leaking oils • Pneumatic: clean and fast and can be used for high speed and/or high load-carrying capabilities but it is difficult to control because air is a compressible fluid
Workspace Geometry	• Reachable workspace: the volume of space within which every point can be reached by the end effector in at least one orientation • Dexterous workspace: the volume of space within which every point can be reached by the end effector in all possible orientations
Motion Characteristics	• Spatial manipulator: at least one of the links of the mechanism possesses a general spatial motion • Links of Spherical robotic manipulator executes spherical motion around a fixed point. • Planar manipulator: all the moving links move in planes parallel to one another.

in some applications the dynamics might not be accurately captured. More realistic representations of real-world systems can be obtained with flexible-link and rigid-flexible link manipulators, but they demand more sophisticated modeling methods [11]. It is worth noting that the particular equations of motion for each kind of manipulator are dependent on a number of variables, including the type of joints, the number of degrees of freedom, and the geometric and material characteristics of the links. **Table 3** provides an overview of the rigid-link, flexible-link, and rigid-flexible link types of manipulators from a modeling perspective. While the mathematical intricacies associated with robotic manipulators are elaborated in **Table 4**.

Mathematical intricacies related to robotic manipulators are crucial for modeling and controlling the manipulator's behavior. By addressing these intricacies, researchers can design effective control schemes, optimize manipulator performance parameters, and facilitate a variety of robotic applications.

TABLE 3. Overview of different types of manipulators from a modeling perspective [5], [9], [12], [13], [14], [15].

Manipulators	Overview	Modeling Approach
Rigid-Link [2]	They consist of a series of rigid links, connected by joints, that do not deform significantly under external load. The position, velocity, and acceleration of the links are determined based on the joint angles and applied forces.	• **Kinematics** Joint angles and link lengths are used to determine the end effector's position, velocity, and acceleration. • **Forward Kinematics** The transformation matrix represents the end-effector position and orientation • **Reverse Kinematics** -Determining joint angles given the desired end-effector pose. -Using geometric methods or numerical techniques to solve for joint variables • **Dynamics** They deal with the forces and torques applied to the manipulator while taking joint contact forces, external forces, and inertia into account. • **Lagrangian Dynamics** Equations of motion are derived based on the Lagrangian Method • **Assumptions** No deformation in the links to design precise control strategies
Flexible-Link [1], [12]	They consist of links that can deform under applied loads such as bending. This deformation can introduce complex dynamics such as vibration, change in the shape, and deviation from the desired trajectories	• **Kinematics** • ***Rigid-Body Kinematics*** Like rigid manipulators for position and orientation. • ***Deformation Kinematics*** -Introducing additional variables to represent the deformation of flexible links. -Incorporating displacement fields to describe the shape of the flexible components. • **Dynamics** • ***Euler-Bernoulli Beam Theory*** It can be used to model flexible links and additional terms can be included to consider some elements including the bending. • ***Modal Analysis*** They are commonly used to analyze the deformation using mode shapes and natural frequencies such as finite element analysis (FEA). • **Assumptions** Links deform within the linear elastic range. Nonlinear effects may be considered
Rigid-Flexible Link [5–7]	They combine both rigid and flexible elements in their structure. In practical applications, manipulators of this kind are frequently used because they enable a trade-off	• **Kinematics** Combine rigid-body and deformation kinematics • **Dynamics** Integration of rigid-body and flexible dynamics: • Rigid links are modeled using body dynamics like Lagrangian dynamics

TABLE 3. ***(Continued.)*** **Overview of different types of manipulators from a modeling perspective [5], [9], [12], [13], [14], [15].**

	between structural integrity and deformation tolerance.	• Flexible links are modeled using methods from structural mechanics such as Euler-Bernoulli beam theory/FEA • The interaction (coupling) between the rigid and flexible elements needs to be considered to capture the overall dynamic behavior • **Assumptions** Linearity of deformation in the flexible links may be considered. Neglecting certain nonlinear effects for simplicity

TABLE 4. **Mathematical intricacies associated with robotic manipulators [11], [16], [17], [18], [19].**

	Intricacy	Description
1.	**Coordinate Systems and Transformations**	Describes the position and orientation in a mathematical framework, relates the coordinate systems, and represents the kinematics. (Transformations involve matrix operations and trigonometric computations)
2.	**Forward Kinematics**	Determines the position and orientation of the end-effector given the joint angles
3.	**Inverse Kinematics**	Computes the joint angles required to achieve a desired end-effector pose (position and orientation)
4.	**Jacobian Matrix**	Relates the velocities of joint angles to the end-effector velocity, crucial for velocity control and path planning
5.	**Dynamics**	Models the relationship between joint torques, forces, and accelerations to understand robot motion and behavior
6.	**Singularities**	Finds configurations where the manipulator loses degrees of freedom.
7.	**Robot Geometry**	Models the manipulator's geometry, including link lengths, joint positions, and end-effector dimensions

There are many different kinds of robots available for industrial operations and manufacturing processes, each with its distinct advantages and capabilities. The most popular type of industrial automation is the **articulating robot** (jointed-arm). It is employed in many applications, such as robotic welding, spot welding, automated assembly, and robotic handling. Another type is the selective compliance assembly robot arm (**SCARA**), which is well-known for its speed and is frequently used for lateral movements and assembly applications. **Delta robot**, also known as a parallel or spider robot, is able to move with incredible accuracy and speed. Manufacturers of electronic, food, and pharmaceutical products frequently use it for automated part transfer and pick-and-place operations. **A cartesian robot**, also referred to as a gantry robot, is affixed to a linear track system. It offers linear movements throughout the track system and can cover tens of meters in a matter of minutes, making it perfect for pick-and-place applications. By working side by side with humans without the need for safety boundaries, the **collaborative robot** has expanded the possibilities for robotic manufacturing. An ideal solution for tight workspaces for automated assembly, robotic coating, or machine tending activities is the **cylindrical robot**, which has a cylindrical work envelope. The **polar robot**, also known as a spherical robot, features a spherical work envelope. It can be used in automated injection molding, robotic die casting, or material handling operations [8], [9].

The motivation for this work originates from the necessity to provide a state-of-the-art review of various control strategies that have been conducted for robot manipulator systems. Based on challenges faced by robot manipulators and other aspects that may affect their performance in effectively accomplishing their tasks, a comprehensive discussion of different control strategies is offered, including the benefits and downsides of each system. Several novel and innovative techniques are also highlighted to guarantee successful operation under varied loading and operating circumstances. In addition, a number of research issues that require further focus are identified. Lastly, some of the off-the-shelf developments in robotic manipulators for research and commercial use are discussed.

The rest of this paper is organized as follows: Section II describes a state-of-the-art review of various control strategies and innovative techniques. Section III shows the discussion, scientific reflections, and future directions. Other related developments are described in Section IV. Finally, the conclusion is illustrated in section V.

II. CONTROL STRATEGIES

Robot manipulators face several obstacles in achieving the accurate control objective of positioning tracking such as load variation, disturbances, uncertainties, friction and coupling, nonlinearity, hysteresis, high-order, and underactuated properties [5], [20], [21], [22]. Therefore, several advanced control strategies have been proposed to overcome these impediments thanks to the prosperous growth in integrated circuits, embedded systems, sensing techniques, and computer technologies in recent years [23]. In this section, a state-of-the-art review of various control strategies and innovative techniques that have been conducted for robotic manipulators is described. This section is divided into four sub-sections, namely, rigid-link, flexible-link, rigid-flexible link, and multi-link (more than two links).

A. RIGID LINK

Rigid-link robot manipulators are considered challenging to control due to some impediments such as external disturbances, uncertainties, coupling impacts, nonlinearity behaviors, and underactuated properties. Several research studies have been performed to enhance system performance and achieve fast response with accurate trajectory tracking.

1) SINGLE-LINK

Starting with single-link rigid robotic manipulators, Bilal et al. [24] investigated the trajectory tracking along with vibrational control of revolute but flexible joint robotic manipulators in the presence of parametric uncertainty. This work has been performed to get vibration-free tracking in a short span of time.

A continuous and bounded jerk trajectory was created and used to execute smooth motion between two points. Additionally, to create a smooth trajectory between two-way points, the proposed technique concatenates fifth-order polynomials. The intended approach is also simple to execute and computationally effective. By conducting numerous experiments on QUANSER's flexible joint manipulator, generated trajectories were effectively evaluated. This research contribution provided vibration-free and smooth tracking precision. Moreover, Wang et al. [25] demonstrated finite time-based sliding-mode control (SMC) to resolve the control limitations of a flexible joint manipulator (FJM) design under strongly coupled states and mis-matched disturbances. Later in the same research contribution, one may see a fixed-time-based observer (FTO) design that tackles these strongly coupled states and disturbances. It has been observed that finite time-based SMC has been proposed to tackle FJM using integral SMC. Within this bi-limit homogeneity and the FTO estimation were included. In this way, the high-frequency oscillations which are commonly known as the chattering effect guarantee finite-time and fast convergence. In addition to this, it has been a successful way to minimize the mis-matched disturbances as well. The theoretical study and numerical results based on single-joint robotic manipulators illustrated that the scheme is comparatively impactful, but it was not validated using a hardware setup, unfortunately. Thus, a robust linear disturbance rejection control (DRC) had been proposed by Wang et al. [26] which was depending on output feedback and was designed with a generalized form of PI observer known as GPIO. It was mainly proposed for the limitation of a n-link FJR system under the impact of time dependent disturbances, model-oriented errors, strong couplings, and unmodeled dynamics. It should be noted that this rejection control scheme is far better than conventional linear active disturbance rejection control (LADRC) because of its method. However, the effectiveness of the proposed strategy has not been verified experimentally.

Boutat-Baddas et al. [27] provided a novel method for designing the H-infinity observer as a new form of a dynamical observer to estimate states of nonlinear Lipschitz systems in the existence of unknown inputs. The usefulness of the suggested observer was demonstrated using a one-link manipulator with revolute joints that was powered by a DC motor system. Based on a comparative study between three types of observers, namely, the generalized observer (GO), proportional observer (PO), and proportional-integral observer (PIO), the generalized observer has the lowest rates, however, the three observers achieve the objective of state estimation. The robustness of the suggested observer with regard to uncertainties and modeling errors is a benefit. Sun et al. [28] proposed a novel dynamic event-triggered robust tracking control approach for a one-degree-of-freedom link manipulator under external disturbance and system uncertainties, using reduced-order GPIO and dynamic event-triggered control (ETC) techniques. Results demonstrate the effectiveness of the proposed strategy in terms of tracking performance, control effort, and robustness to external disturbances. One potential drawback of the paper is that it has only been tested in simulation results, and its effectiveness in practical applications is not yet known Lee et al. [29] proposed a new adaptive gain dynamics control scheme for time-delay systems in robots to improve accuracy and robustness under payload changes. In order to testify to the efficiency of the proposed control strategy a hardware validation has been performed in which a one-link-based arm along with full-arm manipulation had been included. This experimental research work proved to be better in terms of adaptation capabilities and high accuracy for the proposed gain dynamics in the presence of time delays. Though this technique provided better outcomes still there is a lot of evaluation needed for this to be tried in several other scenarios. One may see a new approach proposed by Son et al. [30], it was proposed for a quadratic cost function estimation in the linear optimal control systems utilizing the granular computing neutrosophic environments. In the catalog of several research contributions, one may see the derivatives of fractional order along with neutrosophic Reiemann-Liouville and Caputo fractional derivatives. These techniques provided better solutions and optimal control. Researchers have utilized these techniques in several other electrical drives such as a DC motor embedded with a one-link-based robotic manipulator.

The control idea in the article by Shadrin et al. [31] compensates for external disturbances and strong coupled dynamics. This gives a basic idea of how one may synthesize a motion control strategy for a single-link manipulator even though the equations are non-linear and state-dependent coefficient (SDC). The numerical example demonstrates the system's independence through individual channels, the zero static error in all modes of operation, and the system behavior's correspondence to specified dynamics. It highlights its effectiveness in reducing errors but also notes that it requires accurate knowledge of the robot's kinematics and dynamics.

2) DUAL-LINK

By moving to the two-link robot manipulator, Rawat et al. [32] presented the use of a proportional-integral-derivative (PID) controller to control the trajectory of a robotic manipulator. There are four meta-heuristic algorithms namely sooty tern optimization (STO), spotted hyena optimizer (SHO), arithmetic optimization algorithm (AOA), and atom search optimization (ASO) – have been used to optimize the gains of proportional, integral, and derivative controller for mainly trajectory tracking control of two-link based robotic manipulator. Thus, one may see that researchers have developed a hybrid version of the sooty tern and particle swarm optimization (STOPSO) method which has been compared with the remaining four algorithms. It has been seen that the STOPSO robust results with a minimum fitness value of 0.04541 along with 0.0002 standard deviation. However, the effectiveness of the proposed algorithms needs to be tested in real-world scenarios to validate their practicality. Faraj and Abbood [33] proposed the bat algorithm-based fractional order proportional integral derivative (FOPID) controller for trajectory tracking control of two-link robotic manipulators. A comparative study using the particle swarm optimization (PSO) approach was carried out. The results of simulations have clearly explained the efficiency of the FOPID controller tuned by the bat algorithm compared with the FOPID controller tuned by the PSO algorithm in case of position tracking, disturbance rejection, and friction existence. Unfortunately, the software simulations had not been validated with the hardware setup.

Vafamand [34] derived sufficient conditions of a robust H-infinity non-parallel distributed compensation (PDC) controller design to solve the problem of global stability of the disturbed Takagi Sugeno (T-S) fuzzy systems based on a novel delay-dependent non-quadratic Lyapunov function (NQLF), in terms of linear matrix inequalities (LMIs). In order to testify to the effectiveness of the proposed approach researchers have proposed two simulation cases and the proposed method proved to be better in comparison with the state-of-the-art NQLF techniques, quadratic Lyapunov functions, and last but not least line integral Lyapunov function (LLF) methods. However, this time again the hardware validation with software simulations had not been performed. While performing a literature review one may witness a nonlinear autoregressive moving average-L2 commonly known as NARMA-L2 controller-based torque control strategy which was integrated very nicely with an online version of least square vector (LSV) regression method Şen and Günel [35]. In this technique, machine learning had been utilized to develop the model whereas the two-link robotic arm's simulations were employed to assess the performance in the presence of exogenous disturbances. In this approach, NARMA-L2 responsibly produces better results with no built-in instability like other first and second-order non-linear approaches and systems. In such a scenario where one sees a system with time-varying delays in control inputs as well as in the states of the systems a low complexity state feedback control approach had been introduced by Bikas and Rovithakis [36] for such uncertain multiple input and multiple output non-linear systems. The output tracking faults can have predefined performance attributes applied to them by this controller. Whereas the state measurement delay had been illustrated as a known entity and the control input delay as an unknown constant. Like most of the previous research contributions in the same domain, this technique had been unfortunate to tackle non-linearities. Researchers in this field are always trying to have high precision while tracking trajectories. Thus, an output feedback continuous version of sliding mode control has been developed to address the generic underactuation of the FJR system in the presence of mismatch uncertainties, time-varying external disturbances, and variable operating conditions [37]. A GPIO sort of control has been proposed which proved its claim to validate the comparison tests on a two-link FJR system. It demonstrated robust results even though the system had been induced with multiple matched as well as mis-matched disturbances. The performance had been amazing in that it outperformed the conventional active disturbance rejection control (ADRC). The only deficiency in this research work was the availability of the validation part.

Another approach titled "linear parameter varying-model predictive control (LPV-MPC)" had been proposed for a two-link robot manipulator by [20]. This scheme was optimized using the recently developed transient search optimization (TSO) technique. The TSO-based LPV-MPC scheme outperforms the TSO-based computed torque controller (CTC) scheme in the set-point tracking test and effectively handles uncertainty. The suggested strategy performs better than the metaheuristic algorithm-based CTC systems in terms of maximum overshoot and settling time. This strategy has not yet been tested experimentally or under external disturbances to verify its effectiveness. While studying different research contributions, one may not ignore several high-gain versions of the SMC strategy. Thus, here a super-twisting terminal sliding mode-based robust impedance controller is popular for its robustness in robot-environment interaction. This technique has been proposed by [37]. Simulations on a two-link robot manipulator were employed to demonstrate the effectiveness of the suggested control scheme. Results demonstrate that the suggested approach successfully increases the robustness of impedance control while preventing chattering in SMC. This strategy has not yet been tested experimentally or under external disturbances and uncertainties to verify its effectiveness.

It seems that researchers have been doing a lot of research in several control techniques such as robust-robust, robust-adaptive, adaptive-robust, and adaptive-adaptive control schemes but at the same time, researchers have proposed some disturbance observers and estimators as well such that in [38]. In this work, the researcher proposed an uncertainty and disturbance estimator (UDE) for estimating the noise and fixing it along with an amalgamation with backstepping control (BSC). In this closed-loop system, all of the signals are bounded and neither the output nor the input saturation constraints are broken.

For a two-link industrial robot manipulator (IRM) model affected by parametric uncertainties and external disturbances, Gambhire et al. [39] proposed a continuous super-twisting control algorithm-based integral sliding mode (ISM). Simulation results demonstrate the effectiveness of the suggested strategy in minimizing the tracking error and enhancing overall stability in the presence of uncertain conditions when compared to other controllers, including the conventional SMC, CTC, and nonsingular terminal SMC (NSTSMC). The only drawback or deficiency in this research was the unavailability of hardware validation. Tlijani et al. [40] developed an event-triggered strategy-based time delay SMC (ET-TDSMC) scheme and verified its effectiveness using a two-link robot manipulator via numerical simulation and experimental study. The suggested control mechanism yields acceptable results and could be useful in poor network environments. The suggested controller guarantees a quick convergence rate and high tracking performance, uses fewer network resources, and is better suited for real-world applications. However, the effectiveness of the proposed strategy has not been verified in the presence of external disturbances and model uncertainties.

In order to actively reject disturbances with uncertain boundaries, a class of prescribed time controllers (PTCs) was designed and implemented for a two-link robot manipulator [41]. It has been demonstrated that the obtained PTC is prescribed-time stable if the infinite-time controller (ITC) is asymptotically stable. It is also demonstrated that the suggested approach rejects disturbances with unknown upper bounds and without disturbance observation, making it consistently prescribed-time stable for unperturbed systems and prescribed-time attractive for perturbed systems. However, the effectiveness of the proposed strategy has not been verified experimentally. Through a simulation study, a general control strategy based on the trajectory planning and differential evolution (DE) algorithm for a two-link vertical plane underactuated manipulator (VPUM), without dividing the zone range, avoiding the singularity problem, and fast and smoothly attaining the control objective was presented by [42]. The suggested control method minimizes the control torque while simultaneously drastically reducing control time. Additionally, the results indicate improved robust performance in the presence of external disturbances whereas there was no pulsive change in the torque. Additionally, the complexity of the design has been reduced using a straightforward way to create the tracking controller, which avoids the singular phenomena of the controller in the motion space. However, the effectiveness of the proposed strategy has not been verified experimentally.

Robot-environment interaction control was later investigated by [4]. In this investigation, an issue related to the n-link robotic manipulator was discussed in the absence of force sensors and had been deployed with a new arbitrary time two-layer adaptive version of sliding mode force observer. This is because of the intent to observe and estimate the interaction forces. Simulation results indicate the superiority and effectiveness of the proposed force observer-based control scheme in enhancing performance. However, the effectiveness of the proposed strategy has not been verified experimentally and its effectiveness has not been verified in the presence of disturbances and uncertainties.

While investigating different novel approaches one may come across with fast terminal super-twisting SMC (FTSTSMC) technique proposed by [43]. It was mainly proposed to solve the limitations encountered by a robotic manipulator under parametric noises and disturbances. This technique performs better with the high-order sliding mode observer (HOSMO) in the feedback. The outcomes demonstrate the rapid and precise tracking of the reference signal. Each joint's angles, velocities, and lumped disturbance can be precisely estimated. The suggested method is distinguished by faster tracking speed, smaller tracking error, strong robustness, and chattering reduction. Unfortunately, like previous techniques, this technique did not provide any hardware validation. Without utilizing any mathematical formulas, the trajectory tracking control of a two-link planar robot manipulator was described using MSC Adams and MATLAB co-simulation in the work done by [44].

Researchers may find the SMC and PID control techniques useful in addressing trajectory tracking problems. These techniques have also resolved several issues in terms of settling time, quick convergence rate, and less chattering effect. In order to obtain better performance, the SMC controller parameters were optimized using various optimization techniques, including gradient descent (GD), pattern search (PS), and simplex search (SS). It was finally concluded that the SS technique is much better based on error calculations than the other approaches for tracking the trajectory. This approach has also failed to provide hardware validation in the presence of uncertainties. A leakage type adaptive version of sliding mode (LTASM) has been proposed by Shao et al. [45] to address the tracking control problem of underactuated systems. In addition to this, its effectiveness had been tested using a two-link robotic manipulator. While correlating a conventional adaptive sliding mode (ASM) with integral sliding function-based adaptive SMC (IASM), one may find that the proposed scheme produces less Zeno effect in the presence of actuator saturation. Nonetheless, the efficacy of the suggested approach has not been confirmed when there are outside disruptions.

Pham et al. [46] presented a two-stage flexible joint discrete controller in which the decentralized approach is extended with stiffness to account for the dominant coupling mode. The rigid closed-loop dynamics in the first stage are transformed into the required dynamics by an input-shaping feedforward. In order to improve disturbance rejection, a second stage was introduced. To account for delay and feedback sensor filtering, a generalized smith predictor (GSP) was created. The suggested controller enhances performance in terms of bandwidth, vibration attenuation, and disturbance rejection, according to numerical simulations and experiments on a six-joint robot manipulator. Researchers after using FTSTSMC found another version commonly known as continuous terminal SMC (CTSMC) proposed in [47]. It was a kind of robust finite-time output feedback control strategy. Later in the same research contribution, one may see sliding mode observer (SMO) to tackle the FJM system and the unknown disturbances. In comparison to the conventional ADRC system, results show that the suggested controller has outstanding tracking performance and robustness. Nonetheless, the efficacy of the suggested approach has not been confirmed when there are outside disruptions.

The distributed switched consensus control algorithms have been developed in [48] to acquire cooperative performance while transferring payloads from one place to another. Later researchers found an amalgamation of the average dwell time (ADT) technique with SMC strategy for enhancing cooperative performance. In addition to this, the Lyapunov stability was provided as well. This research was also based purely on numerical simulations only. Even with parameter changes and communication instabilities, the synchronization of the group of manipulators is unaffected. The established consensus tracking technique for manipulators has distinct advantages over its focused on single robot equivalents, including robustness, stability, and effectiveness. Nonetheless, the efficacy of the suggested approach has not been confirmed when there are outside disruptions. A novel method commonly known as inverse kinematics has been presented by [49] in order to address the same issue by utilizing tangential trigonometric models. The strategy involves considering the physical limitations of the robotic arm while optimizing the trajectory of each joint to ensure smooth and precise mobility. The analytical analysis illustrated the approach's efficacy by demonstrating its capacity to effectively and error-free follow complex trajectories. Overall, the method represents an important development in robotic arm control. However, the proposed strategy is computationally expensive and time-consuming.

A robust output-based controller was proposed for a similar sort of robotic manipulator in a master-slave configuration to overcome the challenge of obstacle collision in restricted jurisdiction Cruz-Ortiz et al. [50]. The approach was tested using simulations and experiments on a prototype system. Results show that the proposed control method effectively prevents collisions with obstacles while maintaining the desired trajectory of the slave manipulator. The paper demonstrates the potential of the approach for applications in manufacturing and medical industries. One potential drawback of the proposed method is that it assumes perfect knowledge of the system's parameters, which may not always be the case in practice. Pham et al. [51] suggested a two-stage state feedback (SFB) controller with a disturbance-state observer to control the vibration of a FJM. The first stage used a state feedback controller to stabilize the robot in the absence of disturbances, while the second stage employed a disturbance-state observer to estimate and compensate for external disturbances. Results show that the proposed strategy effectively suppresses vibrations caused by external disturbances. However, the paper assumes known system dynamics and the controller may not be suitable for more complex tasks.

Ling et al. [52] presented a novel adaptive fuzzy command filtered control approach for precise tracking control of n-link flexible-joint robotic systems in the presence of nonlinearity and uncertainty. In the list of adaptive algorithms, fuzzy controllers have been used for a long time to achieve robust tracking along with filtering purposes. This resulted in high tracking accuracy of the manipulator's end-effector in terms of position as well as velocity. Like other research contributions, it was also limited to software simulations only.

Researchers carried out a detailed study of the stability analysis of a robotic manipulator carrying different payloads based on toque control without an adaptive scheme in work done by [53]. The authors proposed a dynamic model of the robot and payload, and used the Lyapunov stability analysis to derive stability conditions for the system. In addition to this, the proposed work also went through the performance evaluation of a two-link planar manipulator moving a point mass as a payload. Results show that the robot can achieve stable and accurate manipulation of the payload without adaptive control. Nevertheless, the suggested strategy's efficacy in the presence of outside disruptions has not been confirmed, which can affect the performance of the robot. Discussing novel sliding mode disturbance observer (SMDOB) based tracking technique for controlling the *Euler-Lagrange* systems in the presence of exogenous disturbances. This research contribution shows a semi-global and exponential control algorithm that ensures the stability of the system and ensures the exponential convergence rate as well for two-link robot manipulators. The best part of this control algorithm is that it does not bother with the dynamics of the system which makes it suitable for other real-world industrial applications. Additionally, the proposed control strategy is simple and easy to implement. Nonetheless, it is important to note that the proposed approach may not be applicable to all *Euler-Lagrange* systems, and further research is needed to test the effectiveness of the proposed approach in real-world applications.

A robust control algorithm was developed by [54] to tackle the issues because of the non-linear dynamics of a system, variable states, and input delays. Later one may study an optimied non-linear SMC as well that has been proposed by [55] for a two-link robot manipulator and has been successful in removing the Zeno effect.

To find the optimal values of the SMC parameters, a PSO algorithm was used. The performed numerical simulations of a two-link robot validate the effectiveness of the proposed control strategy. Compared to other optimization algorithms such as the Genetic algorithm, using the PSO algorithm gives a better quality. FJR has been analyzed for the tracking control issue in the presence of time-dependent disturbances [56]. The virtues of neural networks, disturbance observer (DOB), and ISM were combined in a novel DOB-based neural network integral sliding mode controller with output constraints (DNISMCOC). The radial basis function neural network (RBFNN) has the capability to learn the convergence rate quickly and has a better approximation ability.

Comparisons between DNISMCOC and other cutting-edge controllers demonstrate DNISMCOC's superiority in a number of areas, better tracking performance, and disturbance rejection. However, further validation is needed to assess its effectiveness in practical applications. In the presence of position and velocity constraints, and nonparametric uncertainties, Zhao et al. [57] proposed a novel state-dependent unified mapping function (SDUMF)-based constrained adaptive neural control technique for uncertain robotic manipulators. Through the use of a two-link link robotic manipulator, the effectiveness of the suggested control was verified. To avoid the undesirable, Gambhire et al. [39] proposed a new robust finite-time tracking control technique.

There is a special kind of state observer used along with a filter function to address the Zeno effect. In the work done by [58], the improved chaotic sparrow search algorithm (ICSSA) was combined with the Kent chaotic mapping, Student's t-distribution, and the Lévy flying strategy to provide a swarm intelligence-based method for estimating various system parameters and improving the control precision of robot manipulators. The outcomes show that the ICSSA outperforms other well-known optimization algorithms in terms of competitive results. It is another ground-breaking technique that brings high-level accuracy for the control methods in the domain of industrial manipulators. Later a non-singular Fast terminal SMC control algorithm was hybridized with a wavelet neural network observer commonly known as NSFTSMCW [40]. In this technique, it takes full responsibility for proper joint position whereas it presents it's a lot of impact in reducing the initial stresses so that the convergence rates may tend to zero as soon as possible. In this proposed research work, one may see that this proposed control algorithm can reduce the Zeno effect as well but unfortunately, this algorithm has not been validated with any hardware setup.

Researchers investigated the position tracking control based on an n-rigid link elastic-joint robotic manipulator in which Zaare and Soltanpour [59] proposed an adaptive fuzzy global coupled NFTSMC in the presence of exogenous disturbances. The simulation and practical application of the two-link and single-link elastic-joint robot manipulators tested the effectiveness of the suggested technique. The suggested control not only resolves the singularity and chattering issues but also offers fast tracking while using less energy. The proposed control as a result has a low amplitude and free chattering control input in the existence of uncertainties. However, the effectiveness of the proposed strategy has not been verified in the presence of disturbances. Friction and the joint elasticity coefficient's time-varying influence were also not considered.

Extended Kalman filter (EKF) has been designed with full efficiency by [58] where RBFNN-based soft computing has been hybridized with SMC technique to tackle FJY system under external noises. Results show the effectiveness of the suggested control strategy in suppressing the chattering and eliminating the undesirable effects of the lumped uncertainties. For FJRs with unknown parameters, Huang et al. [60] created an SFB control approach based on adaptive fuzzy compensation. A few simulation experiments were run to show the feasibility of the proposed strategy. In terms of dynamic performance, position accuracy, and robustness to the approximation of link torque, friction torque, and motor inertia, the recommended control technique performs better than other controllers. Zhang et al. [61] suggested a robust fault tolerant (FT) control strategy incorporating Gaussian RBFNN, an adaptive observer, and a NFTSMC for a n-link robotic system in the presence of exogenous disturbances. The proposed neural networks-based FT controller exhibits better performance in simulations on a two-link manipulator, and experiment findings on the *Baxter* robot further support the method's efficacy.

Abdul-Lateef et al. [62] investigated a trajectory method called the linear segment with parabolic blend (LSPB) to describe segments that connect the initial, intermediate, and final points at joint-space planning for a 2 DOF planar robot manipulator in order to solve the problems of improving the optimal trajectory of robot manipulators. Artificial neural network (ANN) controllers were used to generate smooth, valid trajectories in order to control the trajectory. This resulted in increasing effectiveness and eliminated the obstructions. The good part of this research contribution is that it accomplishes the task within a short span of time and without increasing the desired torque value. The implementation of neural networks for the canonical transformation of port-controlled Hamiltonian (PCH) systems has been done by [63]. In this work, researchers have demonstrated an example of a mass-spring system along with an unmanned under-water vehicle and a two-link robotic manipulator design. The outcomes were very impressive in terms of tracking and overall stability. Nevertheless, the suggested strategy's efficacy hasn't been tested in an experimental setting or when there are outside uncertainties or disturbances.

A finite-time robust recurrent neural network (FTRRNN) based on a noise-tolerant formula which was nonlinearly activated, has been proposed with a proven ability to reject all noises and reduce the Zeno effect as well. This model also outperforms the conventional zeroing neural network (ZNN) model in analyzing the ellipse path tracking control for a planar type two-link robotic manipulator as shown in [64]. However, the effectiveness of the proposed strategy has not been verified in the presence of uncertainties. Hwang and Chen [65] suggested a fuzzy fixed-time control (FFTC) to achieve null tracking errors in a finite time. The algorithm used a nonlinear switching surface and a switching gain to ensure the system's stability and robustness to external disturbances. Results show that it outperforms traditional control methods in terms of tracking accuracy, robustness, and convergence speed. However, the algorithm requires prior knowledge of the upper bound of the external disturbance or modeling error, which is not always available in practice.

For nonlinear MIMO robotic systems with unknown control directions and nonparametric uncertainties, Li et al. [66] developed a globally prescribed performance-tracking control technique. Through the use of a two-link robotic manipulator, the effectiveness of the suggested control was verified. The approach was based on an adaptive law and a predetermined performance function combined in a two-stage adaptive control technique. However, additional testing is required to determine its viability in real-life situations. To provide fast and high-precision trajectory tracking under model uncertainty and perturbations. An adaptive non-singular fast terminal SMC commonly known as (ANSFTSMC) has been proposed by [22]. In this research work, a simple demonstration was done utilizing a two-link robot manipulator. The suggested control solution performs more efficiently and with less computing complexity when compared with another strategy, namely, the NSTSMC. The main reason behind this was the unavailability of a piecewise continuous function that should be developed while designing the control algorithm. The proposed strategy, however, has not been tested experimentally. Xu et al. [67] provided a correlation of results between extended state observer-based adaptive backstepping control for robotic manipulators and NFTSMC in the presence of unmodeled dynamics.

Huang et al. [68] investigated the partial and total loss of effectiveness of the actuator failure of robotic systems subjected to dynamic uncertainties by constructing two adaptive neural control schemes, as well a novel neural networks-based DOB was designed to attenuate unknown disturbances. A simulation study on a two-link planar manipulator and an experimental verification on a *Baxter* robot were both implemented for performance evaluation. Thus, it is suggested controllers are capable of simultaneously managing the required performance, the system uncertainties, and the unknown actuator failure. This control algorithm proved the better performance even in the presence of external disturbances and actuator failure. Cruz designed a novel robust finite-time controller to solve the trajectory tracking issue of robot manipulators with full-state constraints based on a state constraint NSTSMC. The suggested method was numerically and experimentally assessed using a two-link manipulator robot. The validation of software results with hardware results supports the effectiveness of the proposed controller by showing improved tracking capabilities. The acquired numerical findings and practical implementation served as further proof of the suggested controller's capability to handle external perturbations. The proposed method guarantees the fulfillment of the full state constraints in the robotic manipulator without excessive consumption of energy. Montoya-Cháirez et al. [69] proposed a novel input-output feedback linearization-based controller, combining the adaptive neural network and model regressor control for flexible joint robots. Its performance was experimentally tested on a two-link FJR. The experimental results validate the proposed theory and the validity of the proposed methodology. The results show that either the friction terms, the unknown dynamic effects, or the parameter value inaccuracies need to be compensated for. However, the effectiveness of the proposed strategy has not been verified in the presence of disturbances.

To execute strong tracking control functions for nonlinear servomechanisms, Chen [70] proposed a DOB-based model reference adaptive control (MRAC), known as the (DOBMRAC) scheme. A MIMO two-link manipulator robot system and a single-input single-output (SISO) mass-spring-damper system were used to test its efficacy. When tracking control performance is evaluated between the classic MRAC and DOBMRAC, the suggested controller shows higher robust tracking control performance for SISO and MIMO servomechanisms with unknown time-varying disturbances, according to the results. Cui et al. [71] introduced a novel adaptive control method combining compliance and vibration suppression modes into a single controller for a FJR to track the target position more effectively in the presence of dynamical uncertainties. Simulation results show how well the suggested control method performs. The proposed control scheme has not considered impediments such as input saturation, input constraints, and unmodeled dynamics. As far as the tracking issue of the manipulator is concerned, one may take into account exogenous disturbances, modeling errors, and motor drive parameters, Zhou et al. [72] proposed an adaptive fuzzy controller. The simulations were performed using a two-link rigid manipulator as an example, and they demonstrate the effectiveness of the designed controller.

For tracking the position of a two-link robot manipulator in the presence of instability problems brought on by external unknown friction, interference, and load variations, Zhou and Wu [73] presented a novel adaptive fuzzy random vector function link (FRVFL) SMC technique. The simulation outcomes showed that the suggested technique is reliable for combined position control and speed tracking. The external friction torque is precisely compensated for, and uncertain interferences are avoided to the greatest extent by integrating the RVFL neural network with the dynamic fuzzy system. Mobayen et al. [74] proposed, analytically and experimentally, an adaptive finite time second-order sliding mode tracking control scheme for n-link robot manipulators in the presence of perturbations. An example of the recommended method's efficacy is provided by a rotating inverted pendulum and a two-link elbow robot manipulator. The suggested controller provides precise tracking control, robust performance, and disturbance attenuation, according to simulation and experimental results. In order to effectively estimate unknown parameters and attain asymptotic stability in the presence of coupled uncertainties, Bagheri et al. [75] designed a regulation-triggered adaptive controller for robot manipulators. A 2-DOF manipulator with four parametric uncertainties was studied to evaluate the performance of the proposed control method. The simulation results show that the controller effectively predicts the unknown parameters while keeping the robot manipulator asymptomatically stable in the presence of parametric uncertainty. However, the effectiveness of the proposed strategy has not been verified experimentally and has not been verified in the presence of external disturbances.

Hendel et al. [76] and Hendel et al. [77] applied an adaptive super twisting-based SMC (AST-SMC) with finite time convergent based on third-order sliding mode linear observer (TOSMLO) for tracking control of an interval type-2 Takagi Sugeno (IT2 T–S) fuzzy model (F-TOSMLO) for a robotic manipulator under uncertainties and disturbances. A two-link robot manipulator was used to test the effectiveness of the suggested control strategy. Results demonstrate the suggested controller scheme's accuracy and robustness performance with a smoothly applied control input. Results indicate that the stability and robustness properties with a reasonable tracking performance are proven in the presence of measurement noise in addition to uncertainties and disturbances under the suggested AST-SMC controller observer architecture. It is suitable for complex nonlinear systems however, the effectiveness of the proposed strategy has not been verified experimentally. Li et al. [3] suggested an arctangent terminal sliding mode surface (ATSMS) and a novel adaptive super-twisting SMC (ASTSMC) to swiftly and precisely follow desired trajectories of IRMs with control backlash. Simulations of a two-link rigid robotic manipulator system were conducted to verify the feasibility of the ATSMS and ASTSMC. Outcomes show that the ATSMS in conjunction with ASTSMC succeed in lowering the control torque amplitude and decreasing chattering while retaining quick and precise trajectory tracking. However, the effectiveness of the proposed strategy has not been verified in the presence of disturbances.

Yih and Wu [78] developed an effective adaptive control method using adaptation laws and a new task-space velocity observer to address the issue of task-space robot tracking control under parametric uncertainties in both kinematics and dynamics. The viability of the suggested adaptive control method for the trajectory tracking of robot manipulators was demonstrated by numerical simulations in which a two-link robotic manipulator had been involved along with a fixed camera that even in the face of kinematic and dynamic uncertainty, the suggested control method successfully achieves the control objective. However, there is no experimental evidence to support the suggested strategy's efficacy, and the paper focused on non-singular Jacobian cases. One of the control strategies in this domain, introduced by Jouila and Nouri [79] is a wavelet neural network (WNN)-based NFTSMC method, identified as (ANFTSMC-C-W) controller. This control algorithm was proposed again for the same two-link-based robotic manipulator to increase the tracking performance under the impact of noises. Results show that the suggested ANFTSMC-C-W controller performs better than certain advanced control techniques described in the literature. Results show that the proposed method is capable of providing high-precision tracking, the convergence rate was also faster along with less Zeno effect. It is clear that the tracking effectiveness can be significantly impacted by the initial values of controller parameters. Unfortunately, there was no hardware validation for the proposed control algorithm.

Zhang et al. [80] proposed an adaptive fractional-order NFTSMC (FO-NFTSM) scheme based on time delay estimation (TDE) for the trajectory tracking control of robotic manipulators. The Zeno effect or chattering noise had been reduced by utilizing the saturation function within the proposed control algorithm. In this research contribution, the same two-link-based robotic manipulator was used. Results indicate that the proposed control approach is more effective and superior to the existing control approaches, specifically the standard NFTSMC strategy and the second-order NFTSMC approach. The suggested approach not only improves the system state's ability to converge, but also avoids the singularity issue, cancels out unknown dynamic model parameters, and eliminates external disturbances. However, there is no experimental evidence to support the suggested strategy's efficacy and it was not tested under the impact of external noises. Later an adaptive finite-time command-filtered backstepping control algorithm was proposed by [81]. It was proposed mainly to tackle external noises and backlash. Thus, its efficacy was tested using PUMA 560 manipulator in simulations. It is clear that the suggested algorithm not only ensures that the closed-loop system has quick convergence performance but also improved tracking performance. The suggested method can guarantee that the position tracking error converges to a desired neighborhood in a finite amount of time in addition to avoiding the explosion of complexity problems for conventional backstepping. However, the effectiveness of the proposed strategy has not been verified experimentally and has not been verified in the presence of disturbances and parameter variations.

One of the adaptive sliding-based neural controls had been proposed by [82] that combined a fast SMC with an ANN for robotic manipulators to achieve fast convergence to the desired trajectory under external disturbances. Results demonstrate the effectiveness of the proposed method in achieving high-precision tracking control for robot manipulators. The only limitation that this technique had, was the need to train the model again and again based on dynamics. Later the same algorithm was amalgamated with a super-twisting version to acquire a more accurate response as shown in [83]. The impact and significance were proved using analytical methods on a two-link-based robotic manipulator. This technique proved to be the one that does not only reduce the error rates but will also enhance the robustness of the entire structure. This approach achieves high-precision control of robot manipulators in the presence of uncertainties and disturbances. However, it requires online learning of the neural network, which can be computationally expensive and time-consuming.

For electrically driven robotic manipulator (EDRM) systems, Peng et al. [84] suggested an adaptive neural impedance control (ANIC) technique based on a neuro-adaptive observer (NAO), taking into account system uncertainties and external disturbances. In one of the simulation-based research works, researchers utilized an electrically powered 2-DOF robotic system to be controlled by the NAO-based ANIC technique. This technique provided the end-effector with desired force tracking and EDRM system position tracking characteristics without detecting velocities and armature currents. Arefinia et al. [85] proposed additionally a robust adaptive model reference impedance controller for a n-link robotic manipulator with parameter uncertainties, actuator saturation, and inaccurate force sensor measurement using a backstepping technique. To verify the effectiveness of the proposed control scheme a simulation study was performed on a two-arm laparoscopic robot. The proposed method demonstrates its effectiveness in improving the tracking accuracy of the robots and reducing the effects of disturbances. Xiong et al. [86] developed a high bandwidth sliding-mode-based link position controller. The extended-regular-form technique and the cascaded control structure based on the sliding-mode estimator approach were employed for the link position tracking control of FJRs. Various reference trajectories and joint stiffness conditions were employed in the simulation to verify and evaluate the strategy. The anticipated strategy demonstrates to be efficient in enhancing the robots' tracking precision and minimizing the effects of disturbances. It is also applicable to several other high-order, nonlinear, uncertain systems.

For impedance control of robotic systems interacting with an environment, Nazmara et al. [87] investigated a regressor-free adaptive model-reference scheme. The gradient descent algorithm in the structure of the fuzzy estimator was employed, allowing for online parameter tuning to reject both parametric and non-parametric uncertainties. On a two-link planar robot manipulator, several simulations as well as a comparison with a positioned-based impedance controller and a regressor-based adaptive impedance controller were performed while taking into account a tunable desired trajectory and various environmental stiffnesses. Results show that the proposed system achieves exponential convergence of the tracking error to zero and a theoretical demonstration of its stability was given.

There is one more amalgamation of a neural network with optimal control technique proposed by [88] for different robotic manipulators under the impact of structured and unstructured disturbances. The optimization of the Hamilton Jacobi Bellman (HJB) equation and SMC strategy were used to derive the optimal hybrid motion/force control, while a RBFNN and adaptive compensator were used to compensate for the system's structured and unstructured uncertainties. There are several research contributions where researchers have correlated simulation results utilizing a two-link manipulator design with this proposed control technique. Trajectory tracking is one of the most frequent issues in this domain of robotic manipulators as they have to perform repetitive tasks in the presence of exogenous disturbances. Thus, Liu et al. [89] hybridized a proportional differential (PD) based feedback strategy having adaptive iterative learning control (AILC) flavor with the neural network. In order to improve the system's learning speed and tracking accuracy, a combined error factor (CEF) was also used for network updating the legislation. This factor is made up of the weighted sum of tracking error and its derivative. Simulation results on a two-link manipulator demonstrate the effectiveness of the proposed control strategies in completing trajectory-tracking tasks. Simulation results demonstrate that the performance of tracking error and learning speed using neural networks is significantly superior to that of the pure controller AILC and other traditional techniques. Nevertheless, there is no experimental evidence to support the usefulness of the suggested approach.

Kahili et al. [90] hybridized fuzzy WNN-based approximator with adaptive control. The proposed method combined the advantages of fuzzy systems, wavelet networks, and adaptive control in order to enhance the controller's performance. to enhance the controller's performance. The hybrid FS-WNN approximator is used to approximate the unknown dynamics of the system, and an adaptive controller is designed to compensate for uncertainties. The effectiveness of the proposed method was demonstrated through simulations on a two-link robotic arm system. The findings demonstrate that, in terms of tracking accuracy and resilience to uncertainty, the suggested strategy performs better than other current approaches. One potential drawback is the complexity of the hybrid FS-WNN model, which may require more computational resources to implement, and train compared to simpler models.

B. FLEXIBLE LINK

The complexity of the mathematical model and the vibrations brought on by the flexible links make controlling flexible link robot manipulators challenging. In order to enhance system performance and obtain swifter responses, numerous research studies have been carried out.

1) SINGLE-LINK

With the single-flexible link robot manipulator as a starting point, de Perre et al. [91] proposed the use of flexible links to increase payload-to-mass ratios for collaborative robots. In addition to discussing the design, simulation, and experimental validation of a flexible-link robotic arm, the paper presented a full assessment of the possible advantages of adopting flexible links. Based on strain measurements, researchers proposed a control algorithm that was proved to be robust for variable changes in payload and had the ability to perform collaborative robotics applications.

The disadvantages of adopting flexible linkages were also highlighted in the paper, including additional complexity, decreased positional precision, and increased energy usage. In this research work, the *Vicon* motion capture system has been used for data acquisition and to properly track the end-effector between the positions of two different link designs. In the beginning, a flexible link-based setup was proposed with a rectangular cross-section and later followed by a cylindrical but again flexible link loaded to see better results of a payload-to-mass ratio.

The performance evaluation of two motion profiles was examined in [92], where the main aim was to lower the vibrational magnitude of a single-link-based flexible composite robotic manipulator. All work and results were proposed based on simulation results only.

For theoretical research, a flexible beam block in *MATLAB/Simulink* was used to develop the *SimMechanics*-based flexible dynamic model, while a layered structural solid element in *ANSYS* was used to establish the finite element model. Experiments were used to validate the simulation results in all motion scenarios. By using simulations and experiments to validate the modeling and analysis of the composite manipulator, the suggested method's level of reliability is raised. One may see a two-nested loop-like control algorithm proposed by [93] and [94]. In this, the proposed control strategy had been derived using singular perturbation theory and embedded with input-state linearization. Hybridized with fractional-order controllers for 2-DOF single flexible link robotic manipulators which were light in weight. They were facing disturbances in actuation because of the strain gauge sensor embedded within them. Results from simulations and experiments demonstrate that these proposed controllers outperform other traditional integer-order controllers of similar complexity and nominal behavior. Raoufi and Delavari [95] proposed, theoretically and experimentally, a novel adaptive FOSMC based on the model-free controller (MFC) approach scheme for effective tracking of the trajectory of a single flexible-link manipulator when there are exogenous disturbances. To estimate the unknown states of the system, the GPIO was designed. The experimental results highlight the system's robustness and well-trajectory tracking. Additionally, the robust performance of the robot against white noise and constant input disturbances was illustrated as well.

Three controller schemes—the linear quadratic regulator (LQR), pole placement, and PID control methods—were used in the work done by [96] to investigate the efficient control method for controlling the position of a manipulator with a flexible link in medical robots and to lessen end effector fluctuations. Results indicate that the LQR control approach gives reliable operations because it offers a better control performance and achieves quicker response when compared to the PID and pole placement methods. However, the effectiveness has not been verified experimentally. Nejad et al. [97] proposed an effective method for precise tip position control of a single-link flexible robot arm under parameter fluctuations and disturbances based on the FOSMC technique. The suggested optimization strategy outperforms the conventional PID control strategy by 56% and 48%, respectively, in the absence of disturbance and the presence of one. The results demonstrate that the proposed control approach is robust and efficient in removing the deflection caused by the flexibility of the connection. However, the effectiveness of the proposed strategy has not been verified experimentally.

Shams and Seyedtabaii [98] proposed an observer-based fault diagnosis algorithm for estimating joint faults in a flexible link robot using a T-S fuzzy observer. The fault was defined by both the multiple proportional–integral (MPI) and algebraic fault models (AFMs). The method is designed to be robust to uncertainties and disturbances in the system and was evaluated using simulations. Results show that the proposed method is effective in estimating joint faults and can improve the performance of the robot in the presence of these faults. However, further experimentation is needed to validate the method in practical applications. Oliveira et al. [99] presented a novel approach to address the challenges faced by inflatable robotic manipulators, which are not very stable after development and have poor deployment precision. An inflatable link that functioned as a compliant structural element, a touch sensor, and an active mechanism for vibration control made up the suggested robot system. In order to monitor structural deformation and identify interaction with the surroundings, the robot also had an integrated visual sensor. By detecting contact with the user, the control system was able to considerably reduce tip oscillations. In order to address control and payload concerns in soft robotics, the research also included inverse kinematics, a pseudo-rigid body model, and techniques for robot state estimation and external force. It is a safe option for activities involving human-robot interaction because experiments on vibration control and inflatable link contact detection show successful performance, including binary detection of touch with the user. Although inflatable manipulators are inherently safe, precisely positioning the end effector is a challenging process that requires control system compensation due to their low structural stiffness.

2) DUAL-LINK

By going on to the two-flexible link robot manipulators, Kayastha et al. [100] presented a comparative study of two composite controllers, SMC with a linear quadratic regulator (SMC-LQR) and nonlinear model predictive control with a linear quadratic regulator (NMPC-LQR), to assess their ability to control the motion of a space robot with two-link flexible arms, affected by an external object. Regardless of the external impact, both controllers correctly track the target trajectory of the robot manipulator and control the post-impact dynamics of the spacecraft. The results also show that the suggested NMPC-LQR scheme performs more accurately than the SMC-LQR technique when there are no uncertainties, while the NMPC-LQR system performs more precisely than the SMC-LQR method under the impact of uncertainties and disturbances. However, the effectiveness of the proposed strategies has not been verified experimentally. Trung and Iwasaki [101] proposed a decoupling control design based on a 2-DOF control scheme for lightweight links and strain wave gears in flexible two-link robots. The manuscript discussed the issue of resonant vibrations that can deteriorate motion performance. The proposed control scheme was based on the H-infinity synthesis. Experiments using a prototype were used to confirm the suggested method's efficacy. The suggested control strategy's effectiveness in precisely meeting the required criteria for the motions under consideration is demonstrated by the results. However, the effects of modeling errors or external disturbances have not been considered.

Model-based joint position constraints had been resolved using controller formulation for robotic manipulators in [102]. In addition to this, one may find the design and corresponding stability analysis within the same research work. To demonstrate the efficiency and viability of the suggested controller, an exhaustive simulation study has been validated with a hardware setup, involving a two-link-based direct-drive planar robot. To deliver elasticity-aware motions for link-elastic manipulators, Krämer et al. [103] presented an online, optimization-based motion planning approach with three distinct objective functions. On an actual manipulator with three actuated DOF and two elastic connections in various disturbance conditions, the approach's efficacy was proved. The findings demonstrate that the amplitudes of disturbance-induced vibrations fade substantially more quickly than with conventional motion planning.

One may find the complete analysis of the planar pick and place parallel manipulator with 2-DOF and flexible limb in [104]. The authors built a prototype and developed a control algorithm based on the kinetostatics analysis to model and validate the manipulator's performance. Experimental results show that the manipulator's positioning accuracy is within the expected range, and the structural compliance allows it to handle unexpected loads without damage. The paper concludes that the manipulator has potential for use in various industrial and research applications. Na et al. [105] proposed a continuum robot (CR) that can be controlled automatically using image recognition and it can operate in narrower spaces than the existing robots composed of links and joints. The kinematics and workspace of the robot were analyzed using the Denavit-Hartenberg transformation and the Monte Carlo method. The paper also provided details on the robot's design and performance testing, where results show that it was able to reach nine targets automatically with errors of less than 10 mm. It is noted that the robot can be operated without the skill level of a human controller, making it an effective tool for minimally invasive surgery.

Niu et al. [106] suggested a broad learning control method for a two-link flexible manipulator with prescribed performance (PP) and actuator faults using a neural network-based adaptive dynamic programming algorithm. The broad learning theory combined with improved RBFNN was constructed in order to mimic the dynamics of flexible robotic manipulators' uncertain model. A simulated analysis was used to test the proposed control approach. Results show that the recommended control strategy is successful in regulating the manipulator with PP and actuator faults. The suggested fault-tolerant PP control also tackles the problem caused by actuator problems, where tracking errors converge into a limited region approaching zero within the given restricted period. A finite-time learning control algorithm has been proposed in [107] for a two-link flexible manipulator in critical conditions like input saturation, output restrictions, and system uncertainty, to achieve quick convergence and vibration amplitude constraint. The simulation results compared to the proportional-derivative (PD) control show how superior the suggested fixed-time control approach is. While preventing the control torque's frequent oscillation, rapid convergence and vibration suppression are achieved. The suggested fixed-time control method eliminates the chattering issue that affects many fixed-time control methods and achieves good tracking performance. The proposed control mechanism can be used on unconstrained systems to some extent as well. However, an optimization algorithm is needed to minimize the energy consumed by joint motors, and the effectiveness of the proposed strategy has not been tested experimentally.

In order to enable vibration suppression while maintaining trajectory tracking, He et al. [108] proposed a novel control algorithm along with hardware validation of a flexible two-link manipulator commonly known as (FTLM) in the presence of disturbances. The special feature of the proposed technique is utilizing online reinforcement learning (RL). The efficacy of the presented control was examined through a series of experiments using the SRV02 *Quanser* Two-Link Flexible Plant. In comparison to the PD controller, the RL control approach can effectively and steadily suppress vibrational levels with high precision and experimental results indicate its practical applicability. However, the effectiveness of the proposed strategy has not been verified in the presence of disturbances.

Ozguney and Burkan [109] proposed the fuzzy logic control rule-based terminal SMC for trajectory tracking control of a flexible link robot manipulator. The obtained results demonstrate the effectiveness of the designed fuzzy logic controller under the influence of exogenous disturbances. In addition, Saidi and Touati [110] created an intelligent control rule for mobile manipulator robots under parametric uncertainties and external disturbances to give a particular level of performance and precise trajectory-tracking missions. For a manipulator robot with two links (Pelican robot), a SMC based on a RBFNN with minimal parameter learning was created. Results demonstrate the proposed control method's effectiveness and reliability in tracking the desired trajectories. Trung and Iwasaki [1] showed an effective two-DOF controller to enable quick and accurate positioning of a light, flexible, two-link robot with elastic joints. This control method was based on a quasi-full-closed-loop control (QFCLC) scheme composed of feedforward (FF) filters based on coprime factorization (CpF) and robust feedback (FB) controllers based on H-infinity synthesis, with the addition of flexible torque compensators for FF coupling based on the three-mass model and an anticoupling-vibration reference filter. The modeling and practical findings demonstrated the capability to acquire the desired performance in comparison with other control algorithms. However, the effectiveness of the proposed strategy has not been verified in the presence of external disturbances and uncertainties.

Yahya and Abbas [111] presented a new hybrid nature-inspired algorithm based on the combination of the salp swarm algorithm (SSA) and grey wolf optimizer (GWO) called the HSSGWOA algorithm, to fine-tune the parameters of the designed integral SMC (ISMC) to enhance the tracking control of the two-link flexible robot manipulator. Results indicate the effectiveness of the proposed strategy compared to other algorithms such as the SSA, GWO, DE, gravitational search algorithm (GSA), PSO, and whale optimization algorithm (WOA), wherein it enhances the performance of the positions of the first and second links by more than 50% and the first and second joints by more than 20%. The suggested strategy's efficacy has not been tested in an experiment, though.

C. RIGID-FLEXIBLE LINK

Due to the need for manipulators that have the advantages of rigid-link and flexible-link such as flexibility and low energy consumption, Zhang et al. [7] proposed a rigid but flexible robotic manipulator that attracted a lot of researchers around. Some research studies have been conducted to achieve the desired performance in different operating conditions. Liu et al. [112] focused on the dynamics and control of a space robot with a long flexible manipulator capturing a non-cooperative space target. According to simulation results, although complicated dynamic behaviors like continuous target collisions and elastic link vibrations may arise from the capturing operation, they also show how well the control technique lessens the impact of the capture on the space robot system.

The control problem for a rigid-flexible two-link manipulator under input quantization was investigated by [14]. In order to offer joint angle control and boundary vibration suppression, a quantized feedback controller was presented in the study. The partial differential equation (PDE) dynamic model for the rigid–flexible system was derived using Hamilton's principle. Simulation results validated the effectiveness of the proposed controller and also showed that border vibrations and tracking mistakes were removed. However, real-time implementation has not been conducted to validate the proposed control system.

Meng et al. [113] developed a tip position control and vibration suppression approach for a planar two-link rigid-flexible (TLRF) manipulator under a passive first joint. The assumed mode method (AMM) and the Lagrangian modeling method were used to derive the dynamic model. According to this dynamic coupling relationship, the passive rigid link can be controlled indirectly by controlling the active flexible link. A genetic algorithm-based position controller was designed to stabilize the active flexible link and suppress its vibrations. The simulation results show how successful the suggested control strategy is. However, the effectiveness of the proposed control strategy needs to be improved to overcome uncertainties. The proposed method requires further verification through experiments to demonstrate its effectiveness in real-world applications using online algorithms.

Meng et al. [5] presented a motion planning and adaptive tracking controller, called ANN-SM tracking controller, using the RBFNN and the SMC technique to achieve position control and track the planned trajectory of an uncertain TLRF manipulator under unmodeled dynamics, parameter perturbations, and persistent external disturbances acting on the joint motors. In comparison with the PD tracking controller and the nonlinear PD-like (NPD-like) tracking controller, in furtherance of demonstrating the enhanced performance of the motion planning and tracking controller, simulation results validate the efficacy of the suggested control technique. Nevertheless, there has been no experimental confirmation of the suggested strategy's efficacy. In three-dimensional space, for a two-link rigid-flexible coupled manipulator system subject to input limitations and time-varying disturbances, Zhang et al. [7] developed an AILC law. Using Hamilton's notion, a dynamic model of a manipulator system was constructed. In order to track rotating angles with high precision and diminish elastic component vibration, an iterative learning control rule that is based on the disturbance observer was proposed. According to the simulation results, the control rule is quite successful at suppressing elastic deformation and clearly affects how the angle tracking converges. The proposed method requires further validation through experiments to demonstrate its effectiveness in real-world applications.

D. MULTI-LINK

A variety of research studies have been conducted for multi-link robotic manipulators in order to give a broad operating range and a high potential for usage in numerous sectors despite the presence of various obstacles. For safe physical human-robot interaction (pHRI), Hussain et al. [114] presented a novel discrete variable stiffness actuator (DVSA) for a compliant robotic manipulator. To validate these mathematical models and attain optimal control, an experimental approach to system identification for the dynamic parameters was used on the physical model. The novel actuator is unique in that it has a design topology that enables quick changes in stiffness between preset levels without the use of a complicated stiffness tuning mechanism. The system is able to follow the desired trajectory thanks to the application of several control approaches, such as PID, LQR, and pole placement. The outcomes highlight the actuator's high potential for use in compliant manipulators. A case study of weight-bearing activity was described as an application of DVSA in human augmentation tasks.

Yamine et al. [115] presented the development of an affordable device, namely *PLANarm2*, aimed at facilitating the upper-limb neurorehabilitation process at home. A 2-DOF five-bar parallel kinematic system serves as the device's foundation. Asymmetrically distributed kinetostatic behavior with regard to the sagittal plane is an essential feature of its symmetric kinematic structure. The measured performances of several active and passive controller types demonstrated good dynamic behavior. The outcomes of the experimental evaluations support a level of performance that is acceptable given the demands of the application being studied. For cable-driven parallel manipulators (CDPM) in the presence of sagging, Luan and Thinh [116] presented an innovative process that combines analytical and empirical methods to generate quasi-static and inverse kinematic models. The resulting model expands for spatial CDPM and is time-efficient. However, any inaccuracies in the model or measurements can lead to errors in trajectory tracking.

EL-Tehewy et al. [117] described a mathematical model for a closed-chain pantograph mechanism that takes into consideration the boundary conditions. Two different controllers were designed, namely, A nonlinear PID (NLPID) controller whose parameters were adjusted using flower pollination (FP) optimization and a PID controller optimized using FP optimization. The findings indicate that when compared to the PID controller, the NLPID controller performs better, requires less rise time and settling time, and has higher accuracy. However, the effectiveness of the proposed strategy has not been verified experimentally. Prasad et al. [118] developed a unique Lyapunov-based control approach to address the motion planning and control issue of a three-dimensional articulated mobile manipulator comprising a car-like mobile platform and a three-dimensional n-link articulated arm considering all mechanical singularities and velocity restrictions. The novel continuous, acceleration-based, nonlinear, time-invariant control laws were supported by theoretical arguments and computer simulations.

For the position-posture control of a three-link planar underactuated manipulator (PUM) with the first free joint under external disturbances, Zhang et al. [119] developed a novel one-stage control strategy. Using a chaos PSO approach in offline mode, the parameters of the trajectory planning method were optimized. To obtain high trajectory tracking accuracy, the nonlinear DOB-based fast terminal sliding mode tracking (FTSM) controller. Results demonstrate the effectiveness and superiority of the suggested control strategy while considering external perturbations. As a result, any initial condition and target state can be achieved using the suggested control approach. But an experiment hasn't been conducted to confirm the suggested strategy's efficacy, and in the presence of uncertainties.

Regarding an innovative parallel robot featuring extremely flexible linkages that are managed by a real-time model inversion that encompasses all the dynamics of a flexible multibody system, three approaches were proposed in the work done by [120]. In the beginning, output redefinition was implemented by directly weighing the rotations and elastic deformations of the links. Second, a small counter weight that has a negligible impact on the eigenfrequencies was fastened to the robot in a useful location. Finally, Using the degree of freedom of the end-rotational effector and a small rotating motor motion, the internal dynamics of the inverse model were stabilized. Compared to conventional rigid body inversion, the experimental end-effector tracking performance based on the three minimum phase algorithms is better and approaches the anticipated trajectory.

By using lightweight micromotors and a novel bioinspired control methodology, Feliu-Talegon et al. [121] presented a mechanical design of a manipulator that mimics the skeleton of a bird and explored the control possibilities of adding manipulation capabilities to ornithopters (flying robots). The suggested approach is feasible, as demonstrated by the positive results of the experiments. The need for lightweight constrains the frame size and necessitates the usage of tiny motors. Huang et al. [122] provided a general control approach for planar 3-DoF underactuated manipulators with one passive joint. The strategy involves trajectory planning and tracking control, utilizing optimized trajectories designed to ensure all links reach their targets. A SMC strategy was employed to track the required trajectories while a DE algorithm was used to get the target angles. An analytical study was used to illustrate the suggested strategy. Simulation results confirm that the proposed control method is effective at different positions. However, the more links the manipulator has, the more parameters we need to optimize. Wu et al. [123] proposed a nonlinear control approach based on a back-propagation neural network (BPNN) model for the position and posture control of a planar four-link underactuated manipulator with a passive second link. The neural network was employed to approximate the system's nonlinear dynamics, while a backstepping SMC scheme was used to achieve position and posture control. The efficiency of the suggested control approach to adjust all active links to their target angles was confirmed by the experimental findings. However, the paper did not take uncertainties or disturbances into account.

In order to deal with harmonic noises, Liao et al. [124] developed two harmonic noise-tolerant ZNN (HNTZNN) models for the dynamic matrix pseudoinversion by adopting an adaptive compensation term to remove the impact of harmonic noises and by introducing a Li activation function to enhance the convergence rate. To verify the effectiveness, the HNTZNN models were applied to a four-link planar robot manipulator subjected to harmonic noises. According to the results, the HNTZNN models are superior to a ZNN model without an adaptive compensation term for addressing the dynamic matrix pseudoinverse problem in environments with harmonic noises. Models can also be applied to a wide range of applications. Ba et al. [125] introduced a slender tendon-driven CR for in situ maintenance of aero-engine combustors considering the piecewise-constant-curvature (PCC) assumption mismatch and sections coupling issues by proposing a novel local model-less feedback controller utilizing a fuzzy logic algorithm. Experimental results demonstrate the stability and applicability of the proposed controller and show how effectively it minimizes the section coupling problem when compared to the PCC-based technique. In terms of hyper-redundant and compliant properties, CRs perform better than traditional rigid-link manipulators. The experimental scenario's open configuration was designed to adhere to the VICON system's application condition, which differs from the practical application scenario.

Based on two fuzzy control techniques—the single-stage fuzzy controller (SSFC) and the three-stage fuzzy controller (TSFC)— Gaber et al. [126] presented a unique control strategy for following a robot manipulator's intended trajectory in the face of uncertainty. The robot manipulator was modeled using *Autodesk Inventor-based Matlab Simulink SimMechanics*. As an experimental validation, the gas leak location detection test in an automobile exhaust system was applied using the proposed control strategy-based robot manipulator model. In terms of quick response, the simulation results show that the TSFC-based system outperforms a nonlinear control model and a trained artificial neural network. The experimental validation shows the robot manipulator's capacity to precisely pinpoint the location of the crack with the aid of the CO2 sensor to identify gas leaks. It can efficiently be integrated into real-world applications; however, the effectiveness of the proposed strategy has not been verified in the presence of external disturbances. An integrated optimization approach based on PSO and Bezier curves was presented by [127] for path planning for obstacle avoidance and discrete trajectory tracking of a super redundant manipulator. Based on the results of the simulation, this integrated optimization method may discover the optimal path for the manipulator to follow in order to locate the target as soon as possible, considering joint limitations and obstacle avoidance. The benefit of this approach is that it can be applied to multitarget tracking and obstacle avoidance in three-dimensional environments. It also calculates control joint angles in inertial space and uses a tip-following strategy to guide the manipulator's motion. The particle filter numerical optimization problem's feasible solution, however, was tied to the initial value selection, and the obstacle avoidance method relied on obstacles having spherical profiles.

A hybrid model for sophisticated tendon-driven robots was presented by [128], effectively filling in the gaps left by data-driven learning and pure physics-based techniques. Through tests and simulations, the modeling technique and validation results were provided in the paper. The suggested hybrid model, according to the paper's conclusion, can be utilized for control design and optimization and can offer more precise predictions of the manipulator's behavior. However, the proposed hybrid model may be computationally intensive and may require significant computational resources. For online left and right Moore-Penrose inversion, Lv et al. [129] presented two novel neural networks (NNNs), namely NNN-L and NNN-R neural models. Applying the suggested NNN-R model to the path-tracking control of a three-link planar robot manipulator was effective. The proposed approach can handle kinematic redundancy and singularities while achieving precise tracking control. However, the approach requires a large amount of computational resources and has limited testing in practical applications.

To simulate the movements of a scrub nurse robotic (SNR) manipulator, Lashin and Alnemer [130] developed a nonlinear dynamic model. Robot links' movements were controlled by an Arduino, conversely, the arms' angle was optimized by the use of the fuzzy logic control system, but an experimental verification of the suggested approach has not yet been accomplished. The paper did not consider the effects of uncertainties or external disturbances. Guo et al. [131] investigated a different-layer nonlinear and linear equation system (DLNLES) and proposed a novel eight-node discrete ZNN model for the DLNLES. A path-tracking control problem of a four-link redundant robot arm was formulated. The suggested eight-node discrete ZNN model is proven to be valid and superior by numerical findings. Additionally, novel ZNN models for dynamic matrix Moore-Penrose inversion were given by [132]. The proposed two modified ZNN (MZNN) models, namely MZNN-R and MZNN-L models were designed to be robust to noise and capable of finite-time convergence. Based on findings from simulations, the suggested models outperform current approaches in terms of handling noise and producing speedier convergence. Two-dimensional planar three-link and three-dimensional Kinova Jaco redundant robot manipulators were used in the experimental investigation. Both theoretical findings and simulation results prove the viability, remarkable efficacy, and superiority of the proposed models for dynamic Moore-Penrose inverse solution. However, more experimentation is needed to evaluate the model's effectiveness in various scenarios.

Founded on two powerful patterns: the impact of decision-making (fuzzy logic) and the grace of cognitive (brain-emotional learning), Sabahi [133] presented a novel robust self-organizing fuzzy emotional (SFE) technique. To test if the proposed method is applicable, an SFE-based controller was developed for a two-link robot and a 3-PSP spatial parallel manipulator. The priority of the proposed strategy above alternative techniques, particularly in terms of enhancing the capacity to deal with uncertainties, is demonstrated by simulation findings. The suggested SFE approach achieves optimal structures in addition to optimal parameters. However, the effectiveness of the proposed strategy has not been verified in the presence of external disturbances.

Yahya and Abbas [134] proposed the parallelism technique-based Harris Hawks optimization (HHO) technique and tested its effectiveness on a 4-link flexible joint manipulator. The rigid links were controlled by the adaptive output feedback tracking controller, whereas the flexible joints were under the control of the ISMC. With an improvement percentage of 76.72 percent for the first link and 70.91 percent for the first joint when compared to the conventional method, simulation results demonstrate the improved algorithm's capability. For use in challenging and constrained settings, Xu et al. [135] created a cable-driven snake-like manipulator with a high load capacity and precise end positioning. In the paper, an adaptive control strategy based on model identification and reinforcement learning was presented, with the tension serving as both the system state variable and the reference model input. Additionally, the model was confirmed by the authors using simulations and experiments. Based on a comparative study, results show that the proposed method based on model identification has a better effect. However, the manipulator's performance may be limited by the accuracy of the model, which relies on several assumptions, such as the cables being perfectly flexible and the friction forces being negligible.

Shen et al. [136] developed a novel decentralized control strategy with finite-time convergence for trajectory tracking control of a space manipulator. The proposed control scheme was based on the recursive decentralized finite-time control (RDFTC), which reduces the computational complexity and eliminates the need for communication between manipulators. The effectiveness of the approach was demonstrated through simulations. Results show that the RDFTC method can achieve fast and accurate trajectory tracking, even in the presence of external disturbances and modeling uncertainties. However, the proposed strategy requires prior knowledge about the model, and it has not been verified experimentally. Quynh et al. [137] suggested a novel robust adaptive-backstepping-recurrent-fuzzy-wavelet-neural-networks (ABRFWNNs) controller method with a PID controller for robot manipulators with dead-zone nonlinearity, which is a common problem in industrial environments. Analytical and experimental results show that the proposed method enhances the position tracking control in the presence of unknown dynamics and disturbances. ABRFWNNs for IRMs are assured to have the appropriate tracking performance, stability, and robustness.

Adaptive fixed-time fault-tolerant constraint control (AFTFTCC), was introduced by [138] to regulate the trajectory of generalized robots in response to input restrictions. The nonlinear filtering tracking error in the proposed AFTFTCC can influence the system response. Two examples were utilized to show the efficacy and robustness of the proposed control: cooperative control of two planar three-link robot arms and trajectory tracking control of a planar three-link robot arm. Findings demonstrate the higher performance and efficacy of the suggested approach is adaptive and does not require large computation time, making it suitable for real-time applications. For an n-link vertical underactuated manipulator (VUM) with an underactuated joint, Wang et al. [21] proposed a unified and simple trajectory planning-based control method using the DE algorithm. The suggested approach outperforms the active–active–passive–active (AAPA) and passive–active–active–active (PAAA) systems, according to simulation data. In contrast to conventional methods, the suggested method can quickly accomplish the control target and does not require partitioning the entire motion space. The proposed strategy, however, has not been tested experimentally.

A thorough bond graph model of a three-dimensional multi-section bionic manipulator was developed as a hybrid manipulator in the work of [139]. In addition to this, for precise trajectory tracking, a model-based control scheme was developed along with a PID controller for the bionic manipulator. Based on simulation results, the robot tip appears to be following the reference trajectory. The bond graph modeling approach has the benefit of simplifying the modeling process by using sub-models to model the full robot. The suggested strategy's efficacy hasn't been tested in an experiment, though. Kilicaslan et al. [140] examined the motion control and end-effector trajectory-tracking force of a three-link, three-dimensional robot while accounting for measurement noise. The trajectory variables settle on the paths faster, and transient oscillations in force tracking and position are controlled, according to the results.

Towards the end of the task, tracking output oscillations are also suppressed. One of the numerous advantages of this control method is that elastic variables and torques may be easily estimated at the pseudo-static equilibrium using algebraic equations. Additionally, this technique's choice may be quite helpful, particularly if the manipulator's DOF is excessive. Furthermore, when compared to methods that use joint angular variables as the controlled variables, higher tracking accuracy can be achieved. As the work nears its conclusion, noise effects are more apparent in the tracking outputs. With the aid of an IRM, an autonomous robotic system outfitted with robot manipulators and visual servoing systems, as well as a multi-agent control strategy and communication structure, Ionescu et al. [141] focused on the implementation, simulation, and system design of hybrid communication and control for the advanced flexible manufacturing technology at the lab level. When applied industrially in the real world, this real-time technology will boost accuracy, dependability, and efficiency. The study suggested a hardware and software expansion that enables the deployment of a flexible and versatile technology capable of producing various products and of being disassembled to recover parts or repair products that don't meet acceptable quality standards. The work does not address the application of resilient control structures to uncertainty. Gandarias et al. [142] suggested a hybrid, learning-based kinematic modeling technique to enhance the functionality of a conventional open-loop position controller for modular, collaborative variable-stiffness-link (VSL) robots that have links with adjustable stiffness. VSL robot is superior and capable of accurately manipulating the position of the end-effector, compared to a robotic manipulator with 3D-printed rigid links.

Robotic manipulators have been extensively controlled using metaheuristic optimization methods. These methods seek to enhance the manipulators' performance by optimizing their control parameters. For this, a variety of metaheuristic algorithms have been employed, such as atom search optimization (ASO), spotted hyena optimizer (SHO), crowd search optimization (CSO), emperor penguin optimization (EPO), satin bowerbird (SB) optimization, DE algorithm, teaching-learning based optimization (TLBO) algorithm, crow search algorithm (CSA), whale optimization algorithm (WOA), bat optimization algorithm, and PSO [32], [33], [42], [111]. These algorithms improve performance measured by performance indices like integral time absolute error (ITAE), integral absolute error (IAE), etc. while supplying the optimal gain values for the control parameters. Using statistical analysis and ranking tests, the efficacy of these algorithms has been assessed [32]. The findings demonstrate how metaheuristic optimization methods, with certain algorithms surpassing others in terms of optimization performance, greatly enhance the control of robotic manipulators.

The PSO method produces superior results when compared to other optimization algorithms as the Genetic algorithm [56]. To stabilize the active flexible link and reduce vibrations, a position controller based on evolutionary algorithms was proposed [113]. Also, Yahya and Abbas [111] provide a meta-heuristic optimization-based control technique using a novel hybrid nature-inspired algorithm based on the salp swarm algorithm (SSA) that is presented to optimize the parameters of the designed ISMC in order to improve the tracking control of a two-link flexible robot manipulator.

In terms of the influence of friction on robotic manipulators, it is considered challenging to regulate precisely positioning and tracking [25]. Variations in load can lead to changes in friction forces, and outside disturbances can compound the effect, causing tracking errors and decreased performance [16]. Attempts at modeling and control are made more difficult by the uncertainty surrounding friction coefficients and changing environmental circumstances [24]. Different models of friction have been developed to represent different features of friction behavior, such as the Coulomb, viscous, and LuGre models [143], [144].

Techniques including feedforward compensation, adaptive control, and observer-based control are used to lessen the impacts of friction [143], [145], [146]. Xu et al. [147] proposed the fish swarm algorithm-based PID controller to regulate a flexible joint robot manipulator and combined inverse control to reduce the vibrational levels. The results show that the control torque curve approaches the pre-set curve, the vibration time is reduced to less than one second, the amplitude is decreased, the joint clearance's impact on the completed surface is lessened, and the response speed is quick enough to satisfy the requirements. While Zhang and Yuan [148] suggested a multivariable feedback controller for a flexible robot under the influence of multiple factors including coupling effect, friction, and terminal load. The findings indicate that as the friction coefficient increases, the vibration amplitude can be decreased. Using the proposed control method, the manipulator's trajectory tracking, and vibration suppression are effective. Furthermore, effective methods including lubrication, the use of precise components, and active dampening systems help to reduce friction-related issues in robotic manipulators [73]. The goal of ongoing research and development in this area is to improve robotic systems' accuracy and dependability, especially for applications that need very accurate tracking and positioning.

A tabular comparison of various control techniques applied to robotic manipulators is shown in **Table 5** which contributes to a more nuanced knowledge of the application of different control algorithms for different robotic manipulators by illuminating the limitations of those algorithms.

When control algorithms are applied to robotic manipulators, they have different limitations, as tabulated in **Table 5**. Although useful, the PID Controller's application may be limited by its inability to handle complex dynamics and different operating/loading conditions.

TABLE 5. Comparison of various control techniques applied to robotic manipulators.

Control Technique	Constraints	Performance Parameters
Proportional Integral Derivative (PID) [32]	- Oscillations - Sensitive to model uncertainties - limited performance for complex systems	• Steady-state error • Stability • Transient response
Fractional Order PID (FOPID) [33]	- Struggled with complex dynamics - Prone to overshooting -Parameter tuning complexity	• Steady-state error • Tracking Accuracy • Robustness
Linear–Quadratic Regulator (LQR) [96]	- Tuning requirements - Complex mathematical formulations - Sensitivity to model uncertainties	• Stability • Control effort • Robustness to disturbances
H-Infinity (H_∞) [27]	- Complex mathematical formulation - Noise sensitivity - Model uncertainties	• Control Effort • Stability • Robustness
Adaptive Control (AC) [70]	- High Computationally demanding - Challenging tuning process - Stability margins	• Stability • Convergence speed • Robustness to parameter variation and disturbance • Tracking accuracy
Model Predictive Control (MPC) [100]	- High computational requirements - Real-time implementation constraints - Sensitivity to model inaccuracies	• Tracking accuracy • Control effort • Robustness
Sliding Mode Control (SMC) [23]	-High-frequency Chattering - Control input constraints - Sensitivity to parameter variations	• Robustness • Fast response • Tracking accuracy • Chattering reduction
Fuzzy Logic Control (FLC) [109]	- Complex rule tuning - Data availability -Computational complexity	• Tracking accuracy • Robustness to uncertainties • Adaptability
Neural Network (NN) [56]	- Requires extensive training data - Model complexity - Overfitting	• Learning rate • Adaptability • Generalization capability
Robust Control (RC) [50]	- Implementation complexity may hinder real-time performance and practical applicability - Actuator limitations	• Robustness to noise, parameter variations, and disturbances • Stability • Position accuracy
Optimal Control (OC) [44]	- May not generalize well to different scenarios or environments - Model uncertainties	• Tracking accuracy • Minimizing control effort • Fast transient response
Iterative Learning Control (ILC) [7]	- Susceptibility to noise, uncertainty, and disturbances - Actuator limitations	• Tracking accuracy • Convergence rate • Robustness to initial conditions

Although adaptive control can adapt to changing system dynamics, it is computationally costly and can cause problems in contexts with limited resources. Although it is noted that MPC takes future system behavior into account and remains a valuable tool, particularly in applications where predictive capabilities and constraints are critical, it may require offline computation, and tuning several parameters [100]. Despite its reputation for robustness, SMC becomes difficult to apply to very flexible limbs since it requires more control effort and suffers from chattering impact. Although fuzzy logic control can handle inaccurate data, its implementation becomes more complex due to the intricate rule tweaking required. Neural network control, which is known to learn and adapt, requires large amounts of training data, which makes it inapplicable in situations where data is scarce. The application of the LQR control to nonlinear contexts is indeed limited by the fact that LQR is specifically designed for linear systems and may not directly address the complexities of nonlinear dynamics. With its complicated mathematical formulation and careful consideration of computer resources, H-infinity Control can be designed to handle disturbances [46].

III. DISCUSSION, SCIENTIFIC REFLECTIONS, AND FUTURE DIRECTIONS

From the previous discussion of the various control strategies for robotic manipulator systems, it can be concluded that linear control systems are characterized by their ability to guarantee the stability of closed-loop dynamic systems in small zones around the operating points or in disturbance-free environments, less energy consumption, low cost, and ease of designing and implementing. However, they are not sufficiently resilient against the various kinds of disturbances and uncertainties, and thus are unable to cover all operating and loading situations. While nonlinear controllers are more effective against external disturbances and uncertainties, and have a larger working range, superior durability, and faster responses. One potential drawback is that they require perfect knowledge of the system's parameters, which may not always be the case in practice. Also, large energy consumption is needed, and adverse effects may occur such as the chattering effect. Adaptive control systems stand out for their robustness, insensitivity to parameters and changes in the external environment, stability guarantee, and superiority in planned tracking. However, they are costly and somewhat complex in practical processes. Intelligent control systems are characterized by a wide operating range and model-free design. However, they need abundant computational resources and professional knowledge for a good initialization. Finally, hybrid control systems are marked by a wide operating range and robustness in the presence of uncertainties and perturbations. However, the key drawback is the limited resources such as the actuator's limited bandwidth.

When aiming for robust performance in robotic manipulators, certain performance parameters take precedence due to their direct impact on the system's ability. **Table 6** describes the superior performance parameters for achieving robust performance in the robotic manipulator. Together, these performance metrics, depicted in **Table 6**, support robotic manipulators' overall robustness, effectiveness, and safety,

TABLE 6. Superior performance parameters for robust performance in the robotic manipulator [11], [18], [149].

	Performance parameter	Description
1.	Position Accuracy	Ability to consistently reach required targets with minimal error.
2.	Trajectory Tracking	Ability to accurately track predefined/reference paths including normal or complex routes
3.	Convergence Speed	Ability to reach targets swiftly and effectively or complete assigned tasks on time
4.	Stability	Ability to ensure stability for safe and reliable operation, particularly during the transient phase or in the presence of disturbances
5.	Disturbance Rejection	Ability to effectively reject external disturbances such as unexpected forces, vibrations, or environmental factors, ensuring precise motion control.
6.	Robustness to Parameter Variations	Ability to maintain stable and accurate performance despite variations in system parameters such as mass distribution, inertia, and friction coefficients.
7.	Control Effort Optimization	Ability to minimize control efforts, such as torque or voltage inputs, while achieving tracking accuracy and reducing energy consumption
8.	Fault Tolerance	Ability to detect, accommodate, and recover from component failures or malfunctions, ensuring continued operation with minimal performance degradation or safety risks

allowing them to do a variety of tasks reliably and precisely. Control schemes and algorithms are developed to maximize these parameters in accordance with the particular demands of the application and the manipulator's capabilities.

As shown in **Figures 3 to 7**, the percentages of papers discussed in this study based on control strategies were displayed using pie charts. link types including, rigid, flexible, and rigid-flexible, robotic manipulator models, which include single-link, two-link, and multi-link models, applications, and DOF. The charts are based on the Web of Science and Scopus databases over the last four years, from 2020 to 2023.

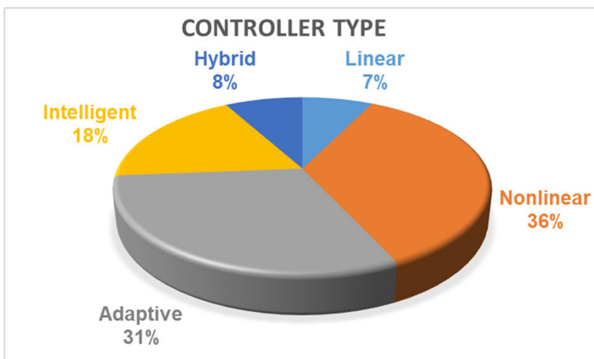

FIGURE 3. Types of control systems including linear, nonlinear, adaptive, intelligent, and hybrid.

Figure 3 shows that nonlinear controllers make up the highest percentage for controlling robotic arm systems with 36% due to fast responses and robustness in the face of uncertainties. Adaptive control strategies come second with 31% which also clarifies their importance in eliminating parameter variation and handling the nonlinear complexity of the robotic system. Intelligent control systems score 18%, indicating their importance in dealing with nonlinear systems, even without having full knowledge of accurate mathematical models. Nonetheless, they have certain disadvantages, including computational complexity, many needed resources, and time-consuming issues for large networks. Ultimately, the hybrid and classic control schemes have the lowest percentages (7 and 8%, respectively), indicating that they are insufficient to govern such complex systems or to meet requirements under various operating situations.

According to **Figure 4**, it is observed that the most used link type of robotic manipulators is the rigid link with 68% while flexible link comes with 18% and the rigid-flexible is with 4%. The reason for that is the flexibility of the rigid link to test novel control strategies due to the simplicity of its dynamic model derivation and its common usage in numerous sectors.

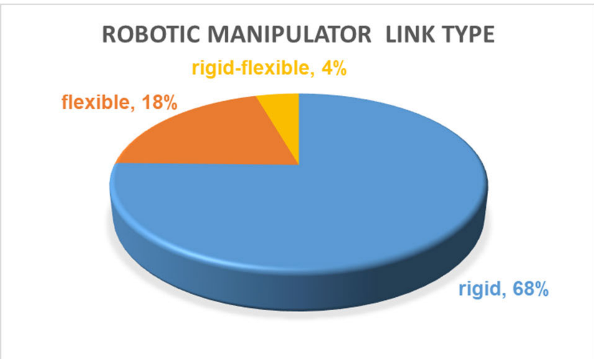

FIGURE 4. Link types of robotic manipulator systems including rigid, flexible, and rigid-flexible.

Figure 5 shows that two-link robotic manipulators account for 59% of all uses, whereas multi-link devices account for 18% and single-link devices account for 11%. This is because they work like human arms, making complicated movements intelligible. They are also utilized extensively in numerous fields, such as pick-and-place robots and surgical procedures.

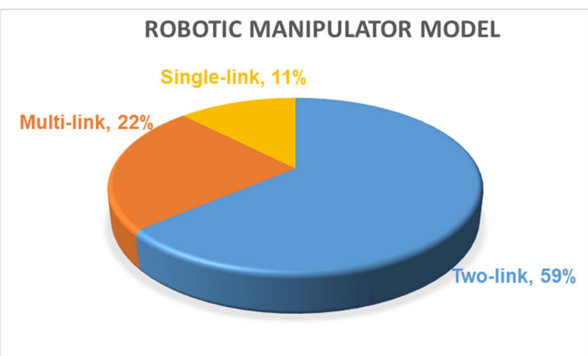

FIGURE 5. Types of robotic manipulator systems including single-link, two-link, and multi-link models.

As shown in **Figure 6, the** result demonstrates that 80% of all uses of robotic manipulators are for industrial purposes, while the remaining 17% are for space applications and the last 3% are for medical purposes. This is due to the fact that they are widely used in a variety of industrial settings, including pick-and-place, assembly, machine tending, packaging, surface finishing, etc.

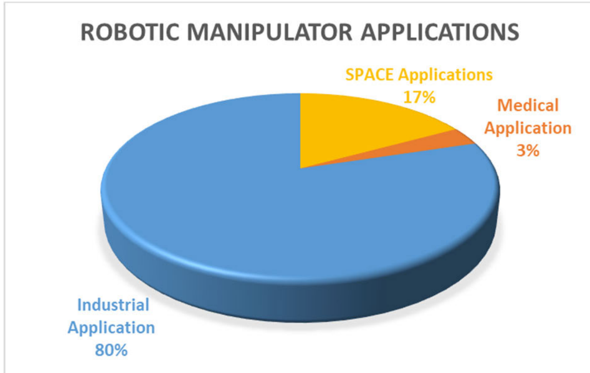

FIGURE 6. Major applications of robotic manipulator systems.

In terms of degrees of freedom, and according to **Figure 7**, results reveal that the most used is the 2-DOF with 71% while the multi-DOF comes with 18% and the 3-DOF and 1-DOF are with 7% and 4%, respectively. The reason for that is its simplicity in understanding the dynamics and the common use of 2-DOF robotic manipulators in testing new control strategies or in several areas, for instance the industrial sector.

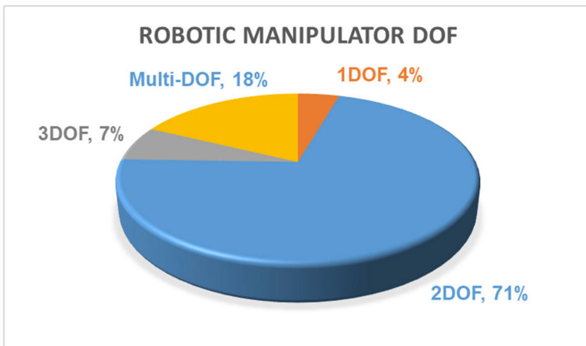

FIGURE 7. Degrees of freedom of robotic manipulator systems.

Kong [150] introduced a comprehensive investigation of the effect of connection parameters on the operation modes of the 3-RER parallel manipulator (PM) in order to provide a solid basis for further research. The planar joint is represented by E, and the revolute joint by R respectively. Using the basic decomposition of ideals and the Gröbner cover, the 3-RER PM has been classified into 13 types. Based on the kind of PMs, the operation mode analysis reveals that a 3-RER PM may have up to 3-DOF or various forms of 4-DOF operation modes.

In relation to countries, academic institutions, researchers, and fields/disciplines often prominent in robotic manipulator research, this paper addressed some general insights. In robotics research, South Korea has become a major player, especially in the field of humanoid robots.

Robotics research groups are active at places like POSTECH (Pohang University of Science and Technology) and KAIST (Korea Advanced Institute of Science and Technology). Japan is also well known for its contributions to robotics, especially in the fields of industrial and humanoid robots. Reputable universities for robotics research include Waseda University, Tokyo Institute of Technology, and the University of Tokyo. In terms of industrial robotics research and development, Germany is regarded as a leader as well. Robotics departments at prestigious universities include Karlsruhe Institute of Technology (KIT), University of Bremen, and Technische Universität München (TUM). The International Federation of Robots (IFR) reports emphasize that a more specialized labor market will result from increased robot use. Based on robot density indicators relevant to the manufacturing business, a global record was set in 2019 for the robotics market. As shown in **Figure 8**, The average global manufacturing-related robot density reached 113 robots per 10,000 people, according to the International Federation of Robotics' 2020 World Robotics Report [151]. **Figures 9 to 11** graphically display the percentages over the last four years using pie/bar charts based on the Scopus databases.

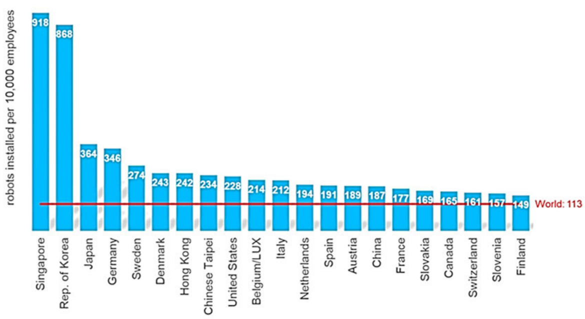

FIGURE 8. Worldwide manufacturing industry-related robot density in 2020 [151].

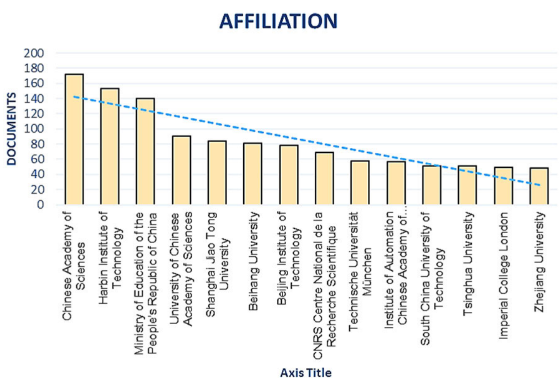

FIGURE 9. Academic contributions by organizational affiliation.

On the flip side, the US has been a major center for robotics research, with a large number of research organizations and universities actively involved in the topic. Notable robotics programs are offered by universities such as MIT, Stanford, Carnegie Mellon, University of California - Berkeley, and Johns Hopkins. But in recent years, China has also made

FIGURE 10. Research works categorized by authors.

significant investments in robots R&D. Robotics research is being conducted in universities like as the Beijing Institute of Technology, Zhejiang University, Tsinghua University, and the Chinese Academy of Science.

Beyond these distinguished institutions, there are a plethora of outstanding institutions, laboratories, and researchers in different countries in this area. Several researchers and experts have authored significant articles and books in this domain, such as Rodney Brooks, Frank L. Lewis, Oussama Khatib, Giuseppe Carbone, Sami Haddadin, etc. Their research encompasses human-robot cooperation, haptics, mobile robotics, robotic manipulators, etc. Countries like the United States, China, Japan, Germany, South Korea, etc. play roles in advancing robotics research with top-tier institutions fostering innovation, in manipulator technologies. These laboratories, researchers, and countries collectively drive progress toward enhancing manipulators across a range of fields including manufacturing automation healthcare, and exploration. **Figure 11** shows that China, the United States, India, and Italy have the highest percentages of academic publications with 36%, 13%, 8%, and 7% respectively. According to **Figure 12**, engineering, computer science, and mathematics comprise the largest percentages of academic disciplines with 34%, 39%, and 15% respectively.

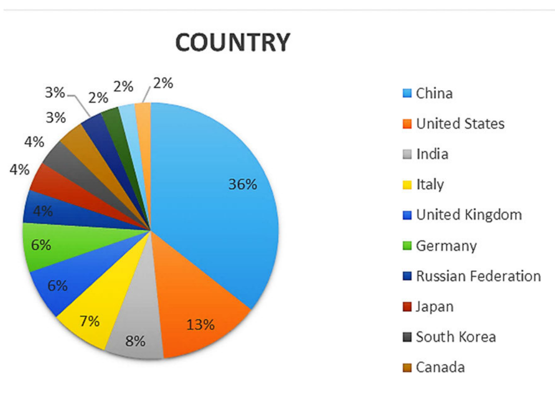

FIGURE 11. Publications sorted by country.

Ueno et al. [152] also proposed the use of a robotic manipulator driven by thrusters for weight reduction and increased mobility. The paper presented the design and development of

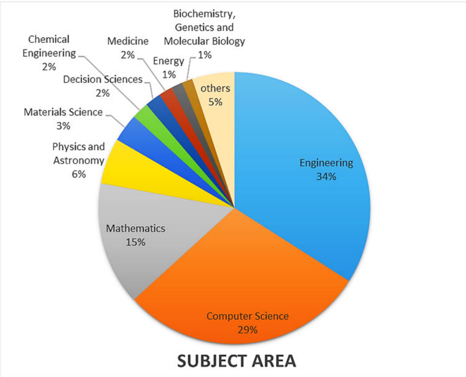

FIGURE 12. Research works based on subject areas.

the *Hiryu-II* manipulator, which has a modular structure that can be reconfigured to suit different tasks. The manipulator's thrusters provide a high thrust-to-weight ratio and precise positioning control. Using a prototype measuring 6.6 meters in length to raise a 0.6 kg payload at the arm end, the viability of the suggested manipulator was demonstrated. The viability of a human-wire-driven, ostrich-inspired manipulator prototype that can move and manipulate deftly without fear of colliding with its surroundings was experimentally studied [153]. A serial chain of eighteen rigid links connected by rotating joints that move in a vertical plane makes up this underactuated manipulator. Operating directly under the control of a human operator, it is propelled by two asymmetric antagonistic wire systems linked to two levers. The studies' results show that the manipulator's tip may achieve a variety of positions, including an upward position defying gravity, illustrating the possible uses for manipulators modeled like ostriches.

Some papers discussed novel techniques, including fruit harvesting [154], spraying process enhancement [155], robotic inspection with obstacle avoidance [156], and pick and place applications [157], [158].

Based on the study, the future directions and challenges related to robotic manipulators can be summarized as follows:

1. Proposing effective control methods for multi-link manipulators with multiple joints underactuated.
2. Suggesting a variety of optimization algorithms to minimize energy consumption by joint motors, such as innovative I-Ching operators, data-based learning methods, and model predictive control.
3. Constructing a system of entirely automated control laws for ostrich robots. Creating a complete system theory for soft robots inspired by ostriches. Building a system of measurement to better understand the flexibility of real ostriches.
4. Controlling of flexible-link manipulators subjected to nonholonomic velocity constraints and persistent unmatched external disturbances.
5. Introducing solutions and constraints to prevent large-scale oscillations generated in manipulators, for example from the state jump caused by the abrupt fault.
6. Designing and controlling 3-RER parallel manipulators and other multi-mode parallel manipulators.
7. Investigating some effective control strategies for a group of robot systems, such as the topology-dependent average dwell time method and adaptive fuzzy output-feedback control.
8. Studying flexible joint robots taking into account input saturation, input constraints, and unmodeled dynamics.
9. Paying attention to the more difficult robotic system with its erratic kinematics, input saturation, unknown parameters, inaccurate force sensor reading, and non-measurable acceleration.
10. Investigating the applications of mobile dual arm for payload carrying using visual navigation.
11. Developing real-time active force control (AFC)-based controllers for robotic manipulators. Considering a wide range of operating and loading conditions, this will offer a very helpful foundation for additional testing of the method's viability in real-world situations.

IV. OTHER RELATED DEVELOPMENTS

There is no question that the industry for robotic manipulators has advanced significantly as a result of the quick development of control theories, electronic technologies, DC motors, 3D printers, sensors, etc. [159]. It attracts both amateurs and industrialists in addition to the academic community. The related off-the-shelf robotic manipulators for a range of uses were presented in this section.

The *Quanser* company created the QArm [160], as shown in **Figure 13**, which is a 4-DOF serial robotic manipulator equipped with a red, green, and blue tendon-based two-stage gripper, blue plus depth (RGBD) camera, as well as the existing 2-DOF robot apparatus [161], for the purpose of engineering education and academic research. Interbotix X-Series arms from *Trossen Robotics* are designed for education and research purposes, with support for robot operating system (ROS) + ROS2, Moveit, Gazebo, and MATLAB [162]. Different models of the Interbotix X-Series arms are available with 4, 5, and 6 degrees of freedom and payloads of 50-750g.

FIGURE 13. QArm robotic manipulator [160].

For industrial sectors, several robotic manipulators can be found such as the Fast Picker, the high-speed robot created by ZenRobotics for material recovery facilities (MRFs), which is ideal for increasing material recovery [163]. Direct Industry company offers a variety of industrial robots, including welding robots, painting robots, palletizing robots, loading robots, and pick-and-place robots [164]. Also, the printed articulated robotic arm (PARA) is a robotic manipulator that provides a cost-effective and robust alternative to existing robotic arms on the market while maintaining sufficient torque and speed [165].

Regarding space purposes, the European robotic arm (ERA) is designed for use in orbit and can anchor itself to the space station and travel hand-over-hand back and forth among fixed points. New ways to operate automated machinery to the orbital complex were established thanks to the ERA. It can be directed from inside or outside the station, and it can be managed in real-time or by preprogrammed commands. It has the capacity to carry out a variety of functions automatically or partially automatically. The Canadarm2 and the Japanese experiment module remote manipulator system are the two robotic arms that are currently aboard the international space station. Both are essential for berthing incoming vehicles and grabbing extraterrestrial payloads on the US and Japanese modules [166].

For medical purposes, There are several robotic manipulators available, including the Burt robot, which can also be used by therapists to help patients with weakness or paralysis in their hands and arms [13], [167]. Due to its human-robot collaboration capabilities, the sensitive seven-axis lightweight LBR Med robot can also provide a wide range of assistance systems in medical technology, such as diagnostics, treatment, and surgical intervention, as shown in **Figure 14**, [168].

FIGURE 14. The LBR Med robot [169].

To enhance working zones, speed, and configuration, several overconstrained robot manipulator types, such as parallel and serial kinds, are also being developed [170]. In factories, robotic arms—also referred to as manipulators—are frequently employed for manufacturing duties. An important area of study for many research publications is industrial robotic manipulators. An autonomous industrial mobile manipulator (AIMM), as seen in **Figure 15**, is the focus of the European SHERLOCK project. Its purpose is to enable safe collaboration between human operators and robots [171], [172].

FIGURE 15. The AIMM robot [172].

An additional article addresses the creation of the robotic arm for collaboration with humans in the industrial environment (RACHIE) as shown in **Figure 16**, an autonomous robotic manipulator with four degrees of freedom that is optimized for smaller jobs and has the ability to identify and classify cans according to color and flaws [173].

FIGURE 16. The RACHIE robot [173].

There are also papers that investigate the design of manipulator clamps. For example, one that provides a manipulator with clamping assemblies and flexible clamping parts to ensure effective clamping and fixation of workpieces [173]. Another manipulator clamp includes a driving mechanism and clamping jaws for adapting to workpieces of different sizes [174]. The developments and uses of industrial robotic manipulators in many settings are highlighted in these studies. Robotics has been increasingly advanced to the point that it is being used in a variety of disciplines, including explorations, medical services, and military fields. In general, robotic manipulators are essential to the industry sectors because they improve accuracy, productivity, and efficiency across a range of operations.

Additionally, xArm is a highly appealing cobot option, as shown in **Figure 17**. It is a low-cost collaborative robot that enables the widespread usage of robotic arms. It is also simple to program, and the assistance is quick and effective. The robotic arm and sensor expansion kit for xArm 1S are included with xArm UNO. The robotic arm on the desktop can carry out a variety of grasping and sorting tasks. A luminous ultrasonic sensor and a color sensor are both included in the sensor development [175].

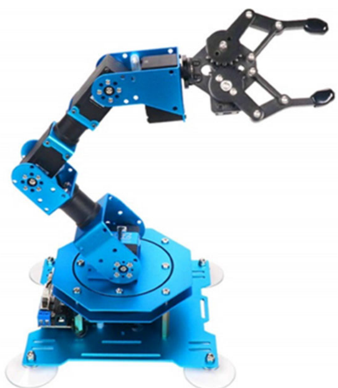

FIGURE 17. The xArm Robot Arm [175].

The PARA is a robotic arm that is more affordable than the currently available versions on the market while yet having enough torque and speed capabilities, as shown in **Figure 18**. The PARA has an end effector speed of 250 mm/s and an accuracy of roughly 2.6 mm in a no-load condition. It can lift a weight of 2 kg at a reach of 940 mm.

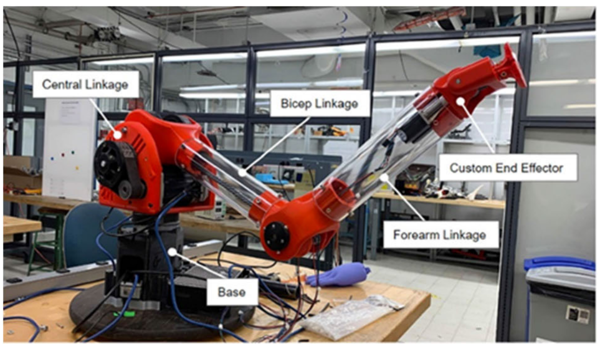

FIGURE 18. PARA's three degrees of freedom [165].

Robotic manipulators have undergone impressive testing and development in recent years. For a variety of applications, researchers are still testing new designs, configurations, and control strategies. Robotic manipulators will continue to advance in terms of safety, speed, size, strength, and intelligence.

V. CONCLUSION

It is indisputable that the innovations of robot manipulators have attracted a lot of concentration due to their numerous applications in diverse sectors. However, they are nonlinear, coupled, and complex systems. This paper presents a state-of-the-art review of various control strategies for robotic manipulator systems under various impediments or adverse operating/loading conditions in order to achieve precise and fast trajectory tracking and overcome obstacles. An overview of the relevant terminology, configurations, components, advantages and disadvantages, and applications is provided at the outset. A cutting-edge review of several control approaches is provided, along with potential solutions when various impediments and challenges are encountered by the systems. A comparative discussion is conducted to present percentages of the papers covered in this study for the different control strategies, link types, models, applications, and DOF for robotic manipulators. Future directions and challenges related to robotic manipulators are additionally presented. Some off-the-shelf innovations in robotic manipulators are lastly discussed for use in academia, research, medicine, and industry.

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