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A Critical Review of Control Techniques for Flexible and Rigid Link Manipulators

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SUMMARY
There is a high demand for developing effective controllers to perform fast and accurate operations for either flexible link manipulators (FLMs) or rigid link manipulators (RLMs). Thus, this paper is beneficial for such vast field, and it is also advantageous and indispensable for researchers who are interested in robotics to have sufficient knowledge about various controllers of FLMs and RLMs as the controllers' concepts are elaborated in detail. The paper concentrates in critically reviewing classical controllers, intelligent controllers, robust controllers, and hybrid controllers for both FLMs and RLMs. The advantages and disadvantages of the aforementioned control methods are summarized in this paper; it also has a detailed comparison for the controllers in terms of the design difficulty, performance, and the suitability for controlling FLMs or RLMs.

KEYWORDS: Control techniques; Flexible link manipulators; Rigid link manipulators.

1. Introduction

Industries and factories highly demand robotic manipulators to take an important role in operations instead of humans especially in dangerous, routine, and difficult tasks. Robots are also demanded to ensure accurate, faster, and economical operations.[1–3] Traditional or conventional robots have been manufactured by rigid links which make them bulky and extremely heavy.[4] The industries require an improvement of the current classical robots in order to reduce the cost of construction, the energy consumption which is caused by big size of actuators, and to increase the productivity. As the traditional robots cannot satisfy the aforementioned requirements of the industries because they are much heavy and bulky, the mass reduction of the rigid robots is highly needed to produce light weight robot manipulators.[5] Decreasing the mass of the rigid and heavy manipulators and producing flexible link manipulators (FLMs) lead to undesirable consequences such as less accuracy or extra deflection caused by the links' flexibility.[6]

FLMs are advantageous and highly demanded nowadays due to several benefits such as high performance, low cost, and less energy consumption due to utilizing small size of actuators.[7] However, the flexible structure of robotic manipulators results in extra difficulty in modeling and control.[8] As FLMs have significant advantages, there has been a rapid increase in the number of researches focusing on modeling and control of FLMs.[9] FLMs currently have high attention in research, this is because their merits which are beneficial in robotic manipulators such as robots of medicine and light weight robots like space arm manipulators,[10] used in plants nuclear, activities of martial, agricultural sectors and homecare.[11] In addition, FLMs are considered safer than rigid link manipulators (RLMs) in order to perform operations near to workers.[12] Moreover, manufacturing industries employ flexible systems in order to maintain the competitiveness of the manufacturing industries, decrease the cost of materials, and enable enterprises to produce closer to demands.[13]

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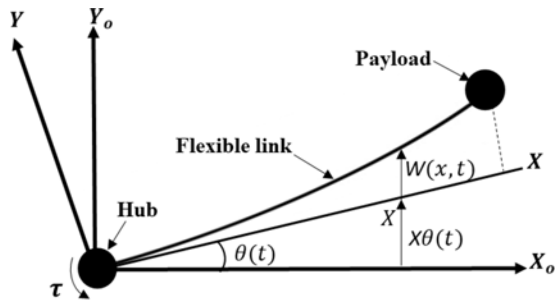

Fig. 1. The schematic diagram of the flexible link manipulator.

Despite FLMs are highly demanded to be employed in several industrial applications due to the beneficial advantages, vibration suppression and controlling FLMs are still huge challenges. Moreover, the existing control algorithms are still not sufficient enough to attenuate the vibrations and to efficiently control FLMs, or they are exceedingly difficult for design and implementation.[14] Due to links' flexibility of FLMs, their dynamical model is much more complicated than that of RLMs. As a result of this complicated dynamic model, several challenges in the design and implementation of controllers are motivated. Moreover, the flexibility leads to undesirable vibrations, which negatively affects systems' performances.[15] Furthermore, the existing control algorithms that have been developed for RLMs do not have the capability to control FLMs since FLMs have infinite degrees of freedom (DOF). Thus, FLMs need particular control techniques in order to make them useful.[16] The complexity of controlling FLMs is because their complicated dynamics and their dynamic equations are nonlinear and strong coupling.[17] Therefore, there are many control techniques for controlling FLMs or RLMs, and an improvement is continuous in order to develop a robust control technique and has to be suitable and easy for real time implementation.

This comprehensive survey aims to review the control methods that have been developed for controlling FLMs and RLMs. The remaining of this paper is categorized into two sections: control of FLMs and control of RLMs, and each section includes classical controllers, intelligent controllers, hybrid controllers, and robust controllers. Eventually, the advantages and disadvantages of all the methods are summarized and the paper is briefly concluded.

2. Control of FLMs

Controlling FLMs is very challenging due to the complexity of the mathematical model and the vibrations caused by the links' flexibility. Figure 1 shows the schematic diagram of a FLM which describes the motor angular displacement, $\theta(t)$, the distance of the rigid body movement, $X\theta(t)$, and the deflection caused by the link flexibility, $w(x, t)$. The total displacement, $y(x, t)$, of any point along the FLM at distance x from the hub is the summation of both rigid body motion, $X\theta(t)$, and the elastic deflection, $w(x, t)$, as expressed in simple form as in Eq. (1) by ref. [18]. Therefore, any proposed controller for FLMs should have the capability for the desired position tracking as well as the vibration suppression.

$$y(x, t) = X\theta(t) + w(x, t) \tag{1}$$

2.1. Classical controllers

Proportional-integral-derivative (PID) is one of the most classical control techniques which is commonly used in several industrial applications due to its simplicity and stability performance.[19] PID controller computes the control signal that activates the real system based on Eq. (2).

$$u(t) = K_p e(t) + K_I \int e(t)dt + K_D \frac{d}{d_t} e(t) \tag{2}$$

$$e(t) = r(t) - y(t) \tag{3}$$

where $u(t)$ is the controller parameter, $e(t)$ is the error, and $y(t)$ is the output. Moreover, K_P, K_D, and K_I are the controller parameters which need to be tuned. Even there are many new control techniques, PID controller is still one of the most widely used controllers in various industrial applications.[20]

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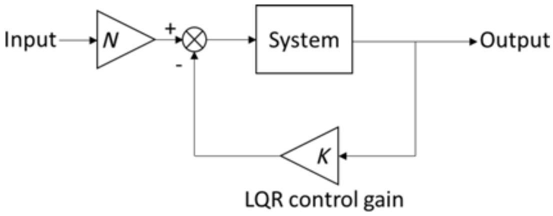

Fig. 2. LQR controller diagram.

More than 90% of industrial applications are still implementing PID controller due to its simplicity of design and implementation, clear functionality, and applicability.[21] A PID and a neural network (NN) were proposed as an integrated controller for input tracking and vibration reduction of two-FLM with varying a tip payload. However, the system takes longer time to reach the steady state while the tip deflection increases with increasing the payload and the performance of motion tracking is insufficient.[22]

A hybrid controller of proportional derivative (PD)-PID was designed for a two-FLM, PD controller for position tracking, and PID controller for vibration suppression. It was demonstrated that the designed controller could track the first flexible link faster and more stable than the second link. In terms of the vibration suppression, the second link had large oscillation and need longer time to totally eliminate the vibrations.[23] Another hybrid controller of PID-PID was designed by Ziegler-Nichols (ZN) and particle swarm optimization (PSO) for the aim of input tracking and vibration reduction for a two-FLM, and the results revealed that the PSO method is better than the ZN method for optimizing the PID parameters. However, the vibrations of the two-FLM are not eliminated in a short time.[24] A PID controller has been optimized by multi-objective differential evolution and the optimized PID controller has been compared with a linear quadratic regulator (LQR) controller.[25] The LQR controller has showed better transient response, and the optimized-PID controller is effective in vibration reduction as has been verified by the simulation and the experimental work obtained.[25]

LQR is a classical optimal controller that normally provides practical feedback gains. The simplicity to design LQR controller and it is straightforward to be used for multivariable system with the same design procedure as for single-input-single-output (SISO) system are the advantages of utilizing it in several applications. The LQR controller gain matrix is presented by Eq. (4) which can be obtained by solving algebraic Riccati equation (ARE) shown in Eq. (5).[26] N is a gain to eliminate the steady state error and obtained by trail and error. The LQR control diagram is shown in Fig. 2.

$$K = R^{-1}B^T P \tag{4}$$

$$A^T P + PA + Q - PBR^{-1}B^T P = 0 \tag{5}$$

A LQR controller was used for reference tracking of angular position and minimizing tip deflection of a single-FLM as mentioned in ref. [27]. Based on the simulation results, the LQR controller produced better settling time, less overshoot for the reference tracking response, and smaller aberration for the tip of FLM compared to a PID controller performance. However, an improvement is required for the system transient response and the tip deflection is not effectively minimized. A LQR controller was also compared with a PID control scheme in terms of position tracking and vibration suppression of a single-FLM; the performance of the LQR controller is better than the PID controller in both the position tracking and vibration suppression.[28] A LQR was integrated with a PID controller; the integrated LQR–PID controller suppressed noticeable amount of vibration of the FLM's tip more than the LQR controller alone, but there is no improvement for the system transient response which was verified via simulation in ref. [29]. Another comparison of a LQR controller with an input shaping controller and a LQR controller with a PID controller was done in ref. [30]; the results showed that the LQR with the PID is more effective for vibration attenuation than the LQR with the input shaping, but the position tracking response is almost the same.

A LQR controller was designed and compared with a state feedback controller which was designed by pole placement method for position tracking and vibration reduction of a single-FLM.[31] In addition, a LQR controller and a pole placement controller were studied in ref. [32]; the results showed that the pole placement controller is better to track a FLM system and to suppress the vibration of

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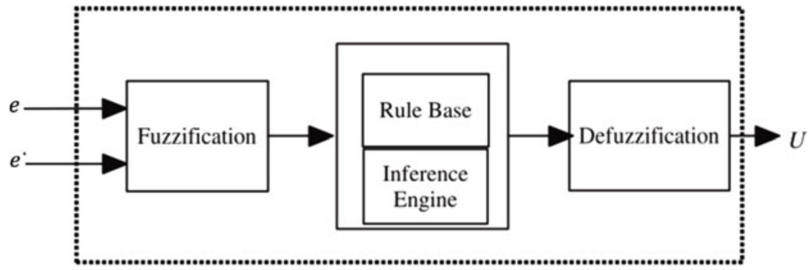

Fig. 3. Fuzzy logic controller architecture.[36]

the tip of the FLM system. A state feedback controller based on the PSO algorithm was compared with a LQR controller for the purpose of positioning the tip of a FLM and reducing its deflection.[33] Moreover, a LQR controller was employed for controlling a single-FLM with a payload in conjunction of utilizing piezoelectric (PZT) actuators in order to minimize the active vibration. However, PZT actuators' placement needs to be optimally located along the FLM for better performance.[34]

2.2. *Intelligent controllers*

Some systems are difficult or impossible to be accurately modeled such as FLMs. So, the design of controllers for FLMs is complicated due to the impossibility of obtaining accurate mathematical models. This critical issue can be overcome by utilizing intelligent controllers such as fuzzy logic control and artificial NN.

2.2.1. Fuzzy logic controller. Fuzzy logic is one of the intelligent controllers which depends on the fuzzy rules that must be systematic and reasonable method; it starts by observing a system and articulates a corresponding system by fuzzy IF–THEN rules. Fuzzy logic controller (FLC) does not stop on the limit of one, zero, and the degree of any element described by 0 or 1. A FLC makes the system closer to people's thinking expression.[35] The FLC has three main components such as *fuzzification*, fuzzy inference engine (decision logic), and *defuzzification* stages. The block diagram of FLC is shown in Fig. 3. The first block in the figure is *fuzzification* which converts each element of input data to degrees of membership by a lookup in one or several membership functions. The rule base and inference base have the capability of simulating human decision-making based on fuzzy concepts and the capability of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. The membership functions of the fuzzy sets and the fuzzy control rules have a big effect on control performance. The third operation is called as *defuzzification*. The resulting fuzzy set is defuzzified into a crisp control signal,[36] where e is the error of an input variable, e^* is the error derivation, and U is the output variable of the fuzzy controller. The number of rules can be increased to get accurate results but it also increases the data processing time.[37]

Normally, it is extremely difficult to obtain a precise mathematical model of real physical mechanisms or machines. This is one of the most basic problems that exist in designing controllers. For this problem, FLC offers a suitable solution by incorporating linguistic information from human experts. Also, another advantage is that FLC can be used to describe human being's vague thinking in a mathematically strict sense.[38] FLC is easy for design and can be realized and implemented by non-experts in control theory. Moreover, FLC is nonlinear, has enough capacity to provide desired nonlinear control actions by carefully tuning its parameters, and is powerful in solving issues which are related to control once the simplicity and fast implementation are required.[39] A single-FLM was controlled by a FLC for tracking the system in straight line paths and minimizing the error of the tip. Based on the simulations results, it can be said that the system performance is not satisfactory.[40] A fuzzy self-tuning PID is a controller that determines the PID parameters intelligently by fuzzy logic method; the parameters are not constant and vary during the controlling process which was introduced in ref. [41]. The fuzzy self-tuning PID was proposed for controlling single link flexible-joint manipulator (single-LFJM) in order to improve the system tracking, and the results demonstrated that the performance is faster and has lower overshoot compared to the classic PID controller.[41] Another fuzzy self-tuning PID controller was also developed for two-FLM and PZT actuators or smart materials were employed for active vibration control. However, the PZT actuators need to study their optimal location along the FLM for better vibration suppression.[42]

A PD-type FLC based on input shaper scheme was developed for controlling the tip angular position of a single-LFJM.[43] After that, a composite of PD-type FLC integrated with non-collocated FLC was proposed for a capable input tracking and vibration reduction of a single-LFJM. The composite of the PD-type FLC integrated with the non-collocated FLC has better ability to effectively reduce the vibration than the PD-type FLC, but it has longer settling time and larger overshoot for the system transient response.[44] An adaptive fuzzy output feedback controller was designed based on a back stepping technique and a dynamic surface control technique for controlling a single-FLM with flexible joint. The adaptive fuzzy output feedback controller can solve the control problem of the single-FLM that has unknown nonlinear uncertainties and does not require all the states of the system to directly be measured.[45] An adaptive neuro-fuzzy controller was applied for controlling a single-FLM with a payload in order to have the advantages of a NN and a FLC.[46] However, the performance of the adaptive neuro-fuzzy controller had slow response and not adequate to suppress the vibration.

A hybrid controller of a PD-type FLC integrated with a non-collocated PID was applied for input tracking and vibration suppression of a single-FLM. The hybrid controller had better performance either for position tracking or to effectively reduce the vibration than a PD-type FLC.[47] Three controllers of FLCs were integrated for the purpose of accurate input tracking and reducing vibration of a single-LFJM. The first two controllers' inputs are the error of the motor rotation angle and its derivative, and the error of the end-effector angle and its derivative, respectively. The inputs of the third controller are the outputs of the first two controllers which produce the final performance of end-point position and vibrations suppression. The performance of the three integrated FLCs was quite good as described by the authors. However, the results reveal that an improvement is required and also obtaining the optimal parameters of FLC is a constraint.[14]

There are also many FLCs have been used for the aim of reference tracking and vibration attenuation of FLMs such as a FLC optimized by modified invasive weed optimization technique,[48] and a FLC was used as a compensator with a nonlinear robust controller.[49] Despite, the FLC is effective and robust for position tracking, vibration suppression of FLMs and has the capability to deal with uncertain disturbances and inaccurate systems, there is still an existing issue which has been addressed by several researchers which is the difficulty of design a FLC for a complicated system with a large number of inputs. Moreover, the total number of fuzzy rules exponentially increases with the number of the system inputs which cause that the FLC is unimplementable.[50]

2.2.2. NN controller. NN is another intelligent controller which is easy and fast for developing without any knowledge of the dynamics behaviors of a system. A NN controller can be built by using only simple information of the relationship between the input and output of a system. Thus, NN controllers are suitable to avoid the difficulty of mathematical modeling especially for systems that are mathematically vague.[51,52] The fundamental architecture of NN includes input layers, hidden layers, and output layers, Fig. 4 shows the architecture of NN.[39] The more the hidden layers, the better the performance of a system. However, training the network takes longer time especially for networks which have many hidden layers.

In ref. [53], a single-FLM with a payload was controlled by an adaptive-NN controller in two types of a full-state feedback control and an output feedback control separately. The full-state feedback and the output feedback had almost the same performance in terms of tracking the desired rotary position. However, increasing the payload caused more overshoot and larger deflection in the tip of the single-FLM.[53] A full-state feedback and an output feedback based on a NN controller were also proposed in ref. [54] for two-FLM for the aim of positioning control and vibration attenuation. Based on the discussed results, the deflection of the second flexible link was larger than the deflection of the first flexible link, but there was a remarkable reduction by employing the NN controller compared to a PD controller. A composite controller of a NN and a disturbance observer (DOB) was designed for controlling a FLM; the proposed controller showed great position tracking performance.[55]

A full-state feedback NN controller and an output feedback NN controller were proposed for a single-FLM with input deadzone for input tracking and vibration restraint. The performance of the

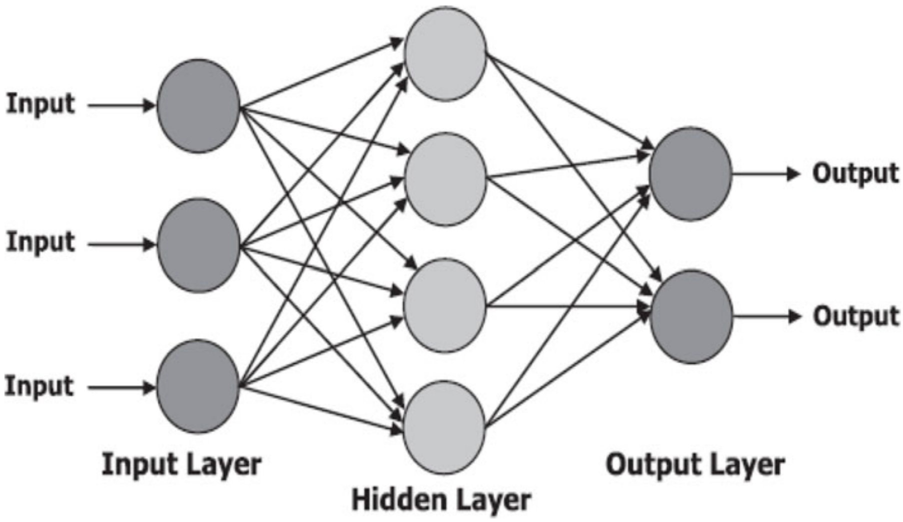

Fig. 4. Neural network architecture.[39]

proposed controllers was superior to a PD controller performance in both input tracking and vibration restraint.[9] A NN with nonlinear controller was integrated to control a two-FLM for damping the vibration with fast transient response. However, more improvement for the system performance is needed.[56] A single-FLM with a variable payload was controlled by a NN-based controller for position tracking and vibration suppression, the proposed NN controller had faster performance in the system transient response and effectively can reduce the vibration of the tip of the single-FLM. However, the computational load is a serious restriction caused by increasing the number of neurons and weights in order to produce satisfactory performance.[57] An integration of a neuro-H_∞ controller was developed based on a singular perturbation to track multi-FLM with flexible joints and to suppress the tip vibrations. The proposed integrated controller was better in tracking the system than an inverse dynamic controller and a LQR controller designed based on the singular perturbation, and was more effective in terms of vibration constraint. The computational weight was decreased by utilizing two-time scale separation of the system complex dynamics.[58]

A multiple NNs controller via feedback-error learning was used in ref. [59] for position tracking and vibration reduction of a single-FLM. Multiple NNs help for obtaining a better-trained neural ensemble which is difficult to be obtained by utilizing one NN. A desired performance of position tracking and vibration suppression was demonstrated in ref. [4] by a fuzzy-NN controller for a single-FLM with a payload. A combined controller of a NN and sliding mode controller (SMC) was implemented for tracking a two-FLM and suppress the tip vibration. A saturation function was used to minimize the chattering phenomenon imposed by the SMC, and two layers of NNs were applied to reduce the computation load.[60] An adaptive NN output feedback controller was developed for the aim of position tracking and vibration attenuation of a multi-FLM in ref. [61].

2.3. Robust controllers

Dynamics of systems are sometimes influenced by uncertainties such as model uncertainties or parametric uncertainties and disturbances to the plant output or associated with the input; also the dynamic variation of systems is a control challenge due to the external environment changes.[62] Thus, robust control techniques are highly required to handle the extra challenges that negatively influence systems. This section concentrates only on SMC, H_∞ controller, and μ-synthesis controller as robust controllers.

2.3.1. Sliding mode controllers. SMC technique has been widely utilized in many of the uncertain systems due to its advantages such as strong robustness, order reduction, easier implementation, and design simplification. To perform SMC design, one needs to first define a switching surface that prescribes the desired convergence property, and then design a SMC to drive the system states to the chosen manifold, which is not influenced by any uncertainty or disturbance. One characteristic of

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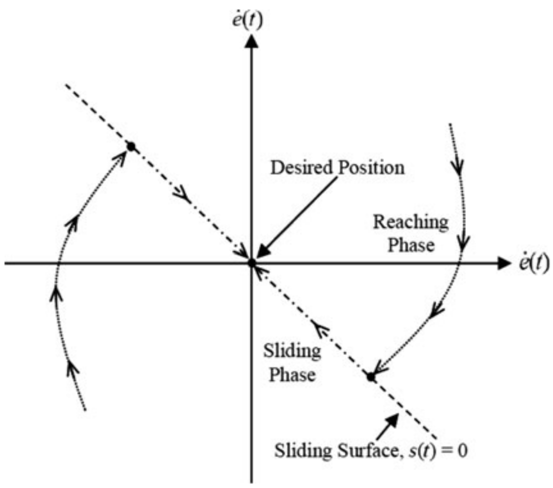

Fig. 5. The general structure of SMC.[64]

the conventional SMC is that the systems usually converge to the equilibrium points asymptotically, and the reason is that the linear switching manifolds are commonly chosen with the asymptotical convergence property.[63] The performance of the SMC depends on designing the sliding surface not the tracking state directly which makes the control technique based on SMC unique opposed to other control techniques. The concept of the SMC is to induce the control signal moving toward the sliding surface and impose the control signal to remain on that surface once it is reached.[64] The SMC general structure is depicted in Fig. 5.

The SMC has been known as a particularly appropriate method to deal with nonlinear systems with uncertainties and disturbances.[65] The study in ref. [66] emphasized that the SMC plays an important role in the theory of variable structure systems and it is appropriate for handling of uncertain nonlinear systems. The SMC has been widely employed to several engineering applications such as robotics, underwater robots, electric machines, automations, and FLMs. A SMC with an observer was designed for position tracking the tip of a single-FLM to a desired position. The observer is to accurately provide the estimated position of the FLM's tip.[67] A fractional order and a SMC were combined as a hybrid controller which has the advantage of robustness for both fractional order and SMC; the PSO algorithm was used to determine the proposed controller parameters.[68] A SMC was compared with a H_∞ controller for controlling a single-FLM under a disturbance and uncertain parameters. The simulation results signified that both the SMC and the H_∞ controller have the same capability in terms of position tracking and vibration attenuation, but the SMC is much easier to be designed than the H_∞ controller.[69] In another comparison of the SMC with a PID controller, the PID controller had better performance in terms of positioning control while the SMC has stronger capability for vibration suppression of the end point of a single-FLM.[70]

A hierarchical SMC was proposed for position tracking and vibration reduction of a single-LFJM which showed better tracking performance and more effective for vibration reduction than a standard SMC.[71] Thereafter, a hierarchical non-singular terminal SMC was developed and had an improvement for the system position tracking over the hierarchical SMC. However, the hierarchical SMC revealed more effectiveness for vibration attenuation.[72] There are other controllers that were designed based on sliding mode technique such as a high-order SMC for a single-FLM,[73] a partially decentralized SMC for a two-FLM,[74] a back-stepping SMC with a DOB for a two-FLM,[75] an optimal second-order integral SMC,[76] and a super-twisting integral SMC[77] for a single-LFJM.

The SMC has a serious issue of the chattering phenomenon which is undesirable oscillations with certain frequency and amplitude caused by fast dynamics or by utilizing digital controllers with limited sampling rate. The chattering harms systems by leading them to an inaccurate performance and causes high heat losses in power circuits.[78] In order to minimize the oscillation caused by the chattering, a Quasi-SMC was proposed in ref. [11] for controlling a single-FLM with variable payloads. Even the Quasi-SMC has less chattering than the normal-SMC, and the chattering phenomenon needs to be eliminated for better accuracy of the system performance. Other techniques were also used to attenuate the chattering such as an asymptotic-SMC[79] and a first-order continuous adaptive SMC.[80]

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A novel controller was developed by combining a non-singular terminal SMC and a high-order SMC based on a Genetic Algorithm (GA) for an optimal system performance.[81] Another non-singular terminal SMC was discussed in ref. [82]. A fractional order SMC was also designed in refs. [83, 84] to control a single-FLM for the purpose of position tracking and tip deflection reduction with less chattering oscillations at the presence of model uncertainties and external disturbances. The proposed fractional order SMC demonstrated better deflection reduction and less chattering than the standard SMC, while the position tracking performance is almost the same.

2.3.2. H_∞ controller. H_∞ controller has the feature of robustness and has a great attention since its inception. It has high capability to deal with different practical and theoretical issues. The H_∞ controller has many advantages over conventional controllers such as providing effective disturbance rejection, dealing efficiently with uncertainties, and high ensuring stability in any operating conditions.[85] A H_∞ controller was designed with a state-dependent Riccati equation technique for a robust position tracking and vibration suppression of a single-FLM. The robustness of the proposed controller for rejecting disturbances achieved with slightly sacrificing the system performance.[86] A comparison of H_∞ controller designed using loop shaping method and linear quadratic Gaussian (LQG) controller for position tracking of a single-FLM showed that H_∞ controller demonstrated better performance.[87] However, LQG performed better than H_∞ controller which was designed using linear matrix inequality (LMI) for controlling a single-FLM.[88]

A H_∞ controller was designed using two methods, mixed-H_∞ method and loop shaping method to accurately track the end effector of a single-LFJM. The results of the system revealed that the loop shaping design method has an improved performance. However, the design of the H_∞ controller based on the loop shaping method depends on the selection of weighting functions which is tedious and time consuming,[89] because there is no systematic formula to select the suitable weighting functions and they are only selected experimentally by trial and error to meet the desired performance.[90] A feed-forward compensator was composed with a H_∞ loop shaping design for better stable system and to effectively eliminate the vibrations as the H_∞ controller-based loop shaping design is only effective to suppress the first vibration modes.[91] A suboptimal H_∞ controller was deigned based on LMI for the purpose of vibration attenuation and disturbance rejection of a single-FLM with a payload, the proposed controller is capable to noticeably attenuate the vibration of the end point of the system and to reject the transient disturbance, the flexible link is attached by a pair of PZT actuators, and the position tracking of the system was controlled by a PID controller.[92] The H_∞ controller can be designed by calculating the H_∞ norm as in ref. [93], and the GA was employed for minimizing criterion of the H_∞ norm of the closed loop system.

An integrated controller of PD-H_∞ was designed for robust position tracking and effective vibration suppression of a single-FLM. The PD controller was proposed to improve the system transient response and the H_∞ controller to effectively suppress the vibrations.[94] A mixed controller of H_2 and H_∞ was designed for position tracking and vibration suppression of a two-FLM. The H_2 was slower for the system transient response and more effective to damp the vibrations while the H_∞ was faster for position tracking; the mixed sensitivity H_2–H_∞ controller has the advantages of both single controllers.[95] Another mixed controller of H_2–H_∞ controller was proposed in ref. [96]. A H_∞ controller was compared with a conventional inversion-based controller with a PID for an accurate position tracking and tip vibration damping of two links flexible joints manipulator (two-LFJM) in the presence of model uncertainties; the proposed H_∞ controller showed satisfactory performance in both position tracking and tip vibration suppression of the system than the traditional inversion-based control.[97] A H_∞ controller was utilized to stabilize the closed loop in conjunction with a causal inversion-based controller which both controllers planned to reduce the tip error of a single-FLM.[98]

A H_∞ control technique based on T-S fuzzy model was proposed to decrease the effect of modeling error induced by the stiffness variety of a flexible joint robot.[99] An integration controller of a H_∞ and a classical PID were developed for robust performance in the presence of model uncertainty; the proposed integrated controller demonstrated the robustness for desired positioning of the tip of a single-FLM.[100] A μ-synthesis-based controller was proposed to robustly modify the input trajectory and reduce the tip error of a single-FLM.[101] Another μ-synthesis robust controller was applied to damp the oscillations of a single-FLM with taking into consideration an external disturbance and model parameter variation; the μ-controller revealed better robustness in disturbance rejections, vibration suppression, and parameter variation than a H_∞ controller as verified experimentally in ref. [102]. The feature of robust controllers over other control techniques is the high capability to deal with systems' uncertainties and to reject external disturbances. However, designing and implementing such aforementioned controllers are difficult and tedious which impose the limitation of using such controllers.

2.4. Hybrid controllers

The combinations of different control schemes are considered hybrid controllers. This type of combination is aimed to suffice the demanded accuracy for some complex systems as single control techniques are not sufficient enough to accurately produce satisfactory performance. A continuous non-singular terminal SMC and an observer-based LQR controller were integrated for controlling a two-FLM.[103] A hybrid controller consists of a nonlinear controller and an adaptive radial-based function NN controller was implemented for tracking a single-FLM and reduce its tip deflection. The nonlinear controller was proposed to produce a stable performance while the adaptive radial-based function NN controller was applied for compensating structured and unstructured uncertainties.[104] An integration of a filtered inverse feed-forward controller and a strain feedback controller was developed for minimizing the transient vibration and residual vibrations respectively of a two-FLM with a payload. The transient vibration is caused by a sudden change in the position of the system, while the residual vibration means that the system needs too long time to reach its stability and perform a task.[105]

A composite controller involves a SMC and a NN was developed to control a FLM for fast and slow dynamics model of the system.[106] Another composite controller was designed in slow and fast timescales based on a dual adaptive dynamic programming which was discussed in ref. [107]. A hybrid FLC was optimized by a GA method in order to optimize the rule base of the FLC. The performance of the hybrid controller is satisfactory in terms of input tracking; a GA-based multi-modal command shaper was applied for better vibration reduction. However, reducing the vibration using the command shaper technique sacrificed the system transient response.[108] A hybrid controller of a NN and a SMC was designed based on a singularly perturbed model of a two-FLM with uncertainties. The hybrid controller had better position tracking performance and more effective for vibration attenuation of the end point than the standard SMC.[109]

A hybrid controller consists of a resonant controller and a FLC as an inner loop feedback and an outer loop feedback respectively.[109] The resonant controller damps the vibrations based on the resonant frequencies while the FLC was employed for the system position tracking. The proposed controller demonstrated good capability to track the FLM and to suppress its vibration. However, increasing the payload results in increment of the system overshoot and the end point vibration.[110] A controller with two stages was developed for precise angular position and damping the residual vibrations of a single-FLM; the first stage is for the angular positioning and the second stage to damp the vibration with employing PZT actuators.[12]

A modified integrated controller of PID and SMC was proposed in ref. [111] for desired trajectory and vibration attenuation of a multi-FLM. The proposed controller gains were optimally tuned using a FLC. The proposed integrated controller showed better performance than the standard SMC and a hybrid fuzzy-SMC control technique.[111] A fractional order was combined with a SMC for input tracking and vibration reduction of a single-FLM; the simulation results revealed the better achievement of the fractional order SMC scheme in terms of faster transient step response, vibration reduction, and smaller chattering than the standard SMC.[84] A combined technique of a finite element model and an advance model predictive controller was developed in ref. [112] for active vibration suppression of a single-FLM. The proposed hybrid control technique demonstrated better capability for suppressing the active vibration of the system in conjunction with employing PZT actuators than the standard model predictive controller.[112] Other hybrid control techniques were proposed for desired position and vibration suppression of FLMs, such as an input shaping with a strain gauge feedback control,[113,114] a strain gauge feedback with a PID controller,[115] a combination of high-order non-singular terminal and SMC,[65] a hybrid of fuzzy non-singular terminal with SMC based on a GA,[116] and an integrated controller of LQ-FLC for a two-FLM which outperformed traditional controller such as PD, LQR, and LQG.[117]

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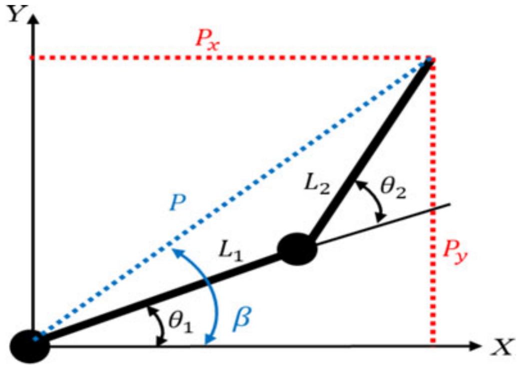

Fig. 6. A schematic of a rigid link manipulator.

3. Control of RLMs

RLMs are easier in terms of mathematical modeling than FLMs which leads to the ease of control. Figure 6 shows a schematic of a RLM, which signifies that the total displacement of the end effector of the manipulator is the only distance moved by the actuators as the manipulator consists of rigid links. Thus, in controlling RLMs no need to consider the links' deflection or vibration during movement and operations. Equation (6) represents the position of the robot tip and Eq. (7) represents the total angular movement, where L_1 and L_2 are the links' lengths.

$$P = \begin{bmatrix} P_x \\ P_y \end{bmatrix} = \begin{bmatrix} L_1\, cos\theta_1 + \ L_2\, cos(\theta_1 + \theta_2) \\ L_1\, sin\theta_1 + \ L_2\, sin(\theta_1 + \theta_2) \end{bmatrix} \tag{6}$$

$$\beta = tan^{-1}\frac{P_y}{P_x} \tag{7}$$

3.1. Classical controllers

PD controllers deal with the transient response of systems regardless of the steady state error and it is useful for fast response systems. A PD controller was used for trajectory tracking of multi-RLM, once the PD was employed with a nominal robot dynamics and then formulated a model independent PD-type output feedback.[118] A PD controller was compared with a PD plus feed-forward controller for controlling two rigid-flexible links manipulator (two-RFLM) which the combined controller performed better than the PD controller alone.[119] Another two-RFLM was controlled by a PD controller in ref. [120]. For an optimized performance, a non-dominated sorting GA was used for tuning a PID controller for controlling two-RLM.[121]

A saturated PID controller was experimentally implemented for controlling a multi-RLM robot with considering the saturations of the control computer output, the servo driver velocity, and the actuator torque.[122] Another saturated PID controller was compared with a classical PID controller in terms of position tracking of a two-RLM.[123] A PID controller was designed in conjunction with a fractional order control approach using PSO and GA tuning methods for a two-RLM. The proposed controller tuned by PSO tuning method performed better in terms of the system position tracking and is easier to be tuned than the GA tuning method.[124] Another fractional order PID controller was tuned using cuckoo search algorithm for position tracking task of a two-RLM which demonstrated better performance than the conventional PID controller.[125] An integration of fractional order and PID was also utilized for improving the position tracking performance of a 3-DOF parallel robot manipulator, and the proposed controller showed faster transient response and less steady state error than the traditional PID control technique.[126] There are also other tuning method to tune PID controller such as ZN, root locus, auto tuning, and Cohen-Coon. Moreover, a new tuning method was proposed to design a PID controller and was applied for controlling a 7-DOF exoskeleton robot.[127] The PID controller was also used for position tracking of three-RLM,[128] and for a robot of 4-DOF.[129]

LQR is an optimal traditional controller designed for the purpose of walking gait tracking for a 5-DOF planar biped robot; the controller demonstrated its ability to track the robot for the walking gait and is able to keep tracking on any input trajectory.[130] The LQR control technique was proposed to control a multi-RLM for various input trajectories and compared with a SMC, the results showed that the SMC has better performance for all kind of inputs.[131] LQG controller has the same structure of LQR controller plus the Kalman filter as an estimator; the LQG controller was also utilized for the purpose of motion planning of a 6-DOF planar robot.[132]

3.2. Intelligent controllers

FLC is a widespread control technique since it has a satisfactory performance for nonlinear systems and is based on linguistic feature. The only limitation of FLC is once the inputs and outputs of a system are increased which impose the difficulty of the tuning process.[36] A FLC was designed using the PSO tuning technique in ref. [36] for positioning tracking of a 2-DOF planar robot which performed better than a PID controller tuned based on the PSO. Thereafter, a FLC was employed to tune the PID parameters as a self-tuning process for controlling a two-RLM which had better stability for position tracking than the classic PID controller.[133] A self-tuning method for a combination control technique of a fuzzy pre-compensated and a fuzzy PID controller was developed and showed its faster response to track a three-RLM better than the combination of the fuzzy pre-compensated and the fuzzy PID controller which was conventionally tuned.[134]

A FLC was designed based on a novel design technique which is the so-called interval type-2 Takagi-Surgeno-Kang for a 2-DOF reconfigurable robot for the purpose of position tracking; the novel proposed FLC had better position tracking accuracy over the interval type-1 Takagi-Surgeno-Kang.[135] A FLC was optimized using three methods such as gradient descent (GD), GA, and modified GA for a parallel robot position tracking. The FLC based on the modified GA demonstrated faster response and better accuracy than the GD and GA technique.[136] An adaptive FLC with a SMC was integrated for positioning control of a 2-DOF robot; the simulation results showed a desired performance. Moreover, the integrated controller of FLC and SMC can be implemented for experimental work as the computational load is very low due to the low number of existing fuzzy rules of SISO form.[137] A decoupled FLC was introduced which is decoupling the multiple-inputs multiple-outputs (MIMO) system into sub SISO systems for position control of a planar RRR robot manipulator.[138]

Due to the simple mathematical models of NNs and the ability to approximate the dynamics of robots and their nonlinearities, NNs are widely employed for controlling robotic manipulators.[139] The research conducted in ref. [139] proposed an adaptive NN control technique with input deadzone to track a 2-DOF robot within constrains; the controller had good performance and could track the robot with the constrains. And a 3-DOF robot was controlled by an adaptive NN controller in ref. [140]. Another adaptive NN controller was designed in ref. [141] to track a 2-DOF robot with full-state constraints and to handle with the system uncertainties and disturbances. Thereafter, an adaptive NN with impedance controller was developed for the purpose of position tracking of a multi-RLM with considering the model uncertainties and input saturation.[142] Another NN impedance controller was also applied to control a 2-DOF robot in terms of reference tracking.[143] A two-RLM robot was also controlled in refs. [144, 145, 146] by an adaptive NN control technique, in ref. [147] by an adaptive NN finite time controller, and in refs. [148, 149] by an adaptive NN integrated with a SMC.

A NN and a FLC were integrated for reference trajectory control of a 2-DOF robot which showed better performance than PID controller.[150] An adaptive FLC integrated with a NN controller was developed to accomplish high accurate position tracking for a two-RLM. The proposed control technique has a nonlinear observer for the purpose of estimating the velocity of the system joints. In comparison with PID, computed torque, and a combined controller of FLC and NN, the proposed adaptive FLC-NN controller demonstrated superior performance in terms of position tracking.[151] A vision-based NN controller designed for robots have uncertainties in kinematics and dynamics which achieved the stability for the position tracking performance.[152]

3.3. Robust controllers

SMC, H_∞ controller, and μ-synthesis controller are the only robust controllers reviewed in this section as they have the ability to handle uncertainties and reject disturbances associated with systems.

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3.3.1. Sliding mode controllers. The classical SMC has unsatisfactory performance of position tracking in the presence of uncertainties and large modeling errors due to using linearized properties of systems by the single model SMC design; this requires high gains in order to ensure satisfactory position tracking performance which leads to chattering phenomenon as discussed in ref. [153]. Thus, a multiple control-based SMC was introduced in ref. [153] to cope the issue of utilizing high gains which was applied for positioning control of a 2-DOF robot. Also it was discussed in the research conducted in ref. [154] that the classical SMC has the disadvantage of chattering phenomenon and a FLC can reduce this issue. Furthermore, the classical SMC is not able enough to handle nonlinear and uncertain robot manipulators. Therefore, an adaptive SMC is demanded to estimate the nonlinearity and uncertainty of systems. The research conducted in ref. [155] used the SMC for trajectory planning of a 2-DOF planar robot in the presence of unknown obstacles.

An adaptive control technique based on SMC has been proposed in ref. [156]; the adaptive SMC was designed for the purpose of position tracking of a 2-DOF robot manipulator which had faster transient response and reduced chattering oscillations than the conventional SMC. Also in ref. [157], an adaptive terminal SMC was introduced for the aim of position tracking for a two-RLM; the proposed adaptive controller has the capability to deal with uncertainties and disturbances and to reduce the chattering impact. Another adaptive SMC was used for a SCARA industrial robot which revealed more accurate position tracking performance and better robustness in dealing with the model uncertainties than the classic SMC.[158] A planar 2-DOF robot was controlled by a novel adaptive SMC scheme which showed its effectiveness for the system trajectory tracking.[159,160] And also a constrained 2-DOF robot was controlled by an adaptive SMC technique in ref. [161]. Moreover, a novel adaptive SMC technique was proposed based on time-delay estimation and combined with a pole placement controller for the purpose of performing precise position tracking of robot manipulators, the proposed control scheme had good position tracking performance and reduced chattering effects.[162]

A self-adaptive SMC was also designed with a FLC in order to possess the advantages of both control techniques and produce an optimal performance for position tracking of a 2-DOF robot manipulator.[163] Also an advanced interval type-2 FLC was integrated with a SMC for the purpose of position tracking of a two-RLM, and the proposed controller has the ability to handle uncertain nonlinear MIMO systems.[164,165] Moreover, an adaptive FLC-SMC control scheme was introduced for reference tracking of a two-RLM with few fuzzy rules in order to reduce the computing time.[166] And an adaptive FLC-SMC was optimized by PSO technique in ref. [167] for controlling an industrial robot. A 6-DOF industrial robot was controlled for position tracking by an adaptive fractional order integral SMC scheme which performed better than the classic SMC.[168] A hybrid controller of SMC and PID was proposed to deal with the model uncertainties and external disturbances and to perform a better stable tracking performance of a 4-DOF robot.[169] In order to possess the simplicity advantage, a PD controller was combined with a SMC; this combination has the linear advantage of PD controller and the nonlinear advantage of SMC. However, the results showed that the SMC alone has better position tracking performance than the combined PD-SMC scheme.[170]

3.3.2. H_∞ controller. Robust controllers have the capability to deal with uncertainties of systems and to reject external disturbances. H_∞ controller is nonlinear and robust and has several methods to be designed such as solving ARE, LMI technique, and loop shaping design technique. Based on solving ARE, a nonlinear H_∞ controller was developed for tracking a 2-DOF robot in the presence of disturbances, and the proposed H_∞ controller showed improved performance compared to PD controller, PID controller, and LQR controller as illustrated in ref. [171]. An adaptive H_∞ controller was introduced for position control of a two-RLM with variable payloads and a disturbance which performed better than a traditional adaptive controller.[172] A H_∞ controller was integrated with a combination of a control scheme of a computed torque control, a NN, and a variable structure control in order to guarantee a robust position tracking of a 2-DOF robot manipulator with parameter uncertainties. The NN was designed to estimate the parameter uncertainties, the VSC was used to attenuate the influence of approximation error, and the H_∞ controller was employed to accomplish the robustness of the tracking performance.[173,174] A H_∞ controller was combined with a fast terminal SMC and a wavelet NN to reduce the influence of approximation errors, quickly minimize the tracking error to a desired position, and estimate the uncertainties and unknown dynamics of a 2-DOF robot respectively.[175]

A robust integrated controller of a FLC and a nonlinear H_∞ controller was proposed for position control of a 2-DOF robot in the presence of structured and unstructured uncertainties. The FLC was utilized for approximation of the structured uncertainties, and the nonlinear H_∞ controller was used to suppress the impact of the unstructured uncertainties and to reduce the positioning error. The proposed robust integrated controller performed effectively in terms of position tracking and dealing with the uncertainties.[176] A comparison between a H_∞ mixed-sensitivity controller and a μ-synthesis controller was analyzed in terms of robust and stable position tracking in the existence of uncertainties and disturbances. The results demonstrated that the μ-synthesis controller had better stability than the H_∞ mixed-sensitivity controller, but the μ-synthesis controller has higher polynomial order.[177] Another comparison between a H_∞ controller and a μ-synthesis controller showed that the μ-synthesis controller is superior in terms of performance and robustness for position tracking of a two-RLM.[178] A H_∞ controller, an integrated H_2–H_∞ controller, and a μ-synthesis were implemented and compared for controlling a 3-DOF robot in terms of position tracking, in which the μ-synthesis had the best performance, but it requires extra essential computational effort for designing process.[179]

3.4. Hybrid controllers

Hybrid controllers have more than one control technique which assists to possess the advantages of all the integrated control schemes and they may solve the problems of each other. For example, SMC is nonlinear and robust, but it has a serious drawback which is the chattering phenomenon. FLC is also a nonlinear control technique and can deal with complicated systems, but it cannot ensure robust performance. So, combining SMC and FLC can guarantee the robustness of the controller and may solve the chattering issue or at least reduce its effects based on the research conducted in ref. [180] for position control of an industrial robot. Also an adaptive integrated controller of FLC–SMC was proposed and has the robustness advantage of SMC and the chattering reduction of FLC which the proposed controller had a better performance position tracking for a 3-DOF robot than the standard FLC-SMC as discussed in ref. [181]. Furthermore, a MIMO adaptive FLC was combined with a terminal SMC which has the merit of reducing the chattering by the FLC and retain the robustness of the SMC. Even the proposed controller had better performance for controlling a 2-DOF robot manipulator with unknown payload than the combination of the adaptive FLC-SMC, and its performance was not satisfactory.[182] The hybrid control scheme of FLC-SMC was also designed and implemented for positioning control of a 2-DOF robot and the fuzzy rules were tuned using PSO technique in order to minimize the steady state error.[183]

An adaptive hybrid FLC-SMC control technique was used for position control of a 3-DOF robot which performed better than a pure SMC and a hybrid controller of FLC-SMC.[184] Changing the payload masses at the end effector of a robot influences the joints motion. Thus, an adaptive integrated controller of a PID controller plus a model reference adaptive controller (MRAC) was proposed to deal with the payload variation and to improve the system position tracking; the proposed controller had a better performance than the PID controller and the MRAC separately as implemented for controlling 1-DOF, 2-DOF, and 3-DOF robots.[185] Model uncertainties and disturbances are serious issues with robotic manipulators and an efficient controller for such systems is highly demanded. Therefore, a combination of a fractional order, a FLC, and a PID were investigated for position tracking and disturbance rejection of a 2-DOF robot which performed better than the FLC-PID, the fractional order-PID, and the traditional PID.[186] An adaptive hybrid controller consists of a joint space adaptive control, and a task space adaptive control was investigated for minimizing the position tracking error once the robot manipulator is affected by surrounding disturbances. The integrated controller demonstrated better position tracking performance than its components.[187]

A two-RLM was controlled in ref. [188] by the combination of a model-based approach, a radial basis function NN, and an adaptive bound part. The radial basis function was employed to discover the uncertain dynamic parameters, the NN was utilized to approximate the error, and the adaptive bound part was used to estimate the bounds on unmolded dynamics.[188] Another two-RLM was controlled by three combined control techniques: a FLC, a PSO technique, and support vector machine (SVM) which named Fuzzified PSO-SVM. The proposed controller is superior over the standard FLC, PSO, and PSO-SVM. However, personal expertise is demanded for optimal tuning of the fuzzy rules.[189] An intelligent hybrid controller was also proposed in ref. [190] which combines a FLC

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Table I. Extra works related to control FLMs and RLMs.

Manipulator type	Control type	Control name	References
FLMs	Classic	PD	[192]
		PID	[193, 194]
		LQR	[195, 196, 197]
	Intelligent	FLC	[198, 199]
		NN	[200, 201]
	Robust	SMC	[202, 203, 204]
		H_∞	[205, 206]
	Hybrid		[207, 208, 209, 210]
RLMs	Classic	PD	[211, 212, 213]
		PID	[214, 215]
		LQR	[216, 217]
	Intelligent	FLC	[218, 219]
		NN	[220, 221, 222, 223]
	Robust	SMC	[224, 225, 213, 226]
		H_∞	[227, 228]
	Hybrid		[229, 230, 231, 232, 233]

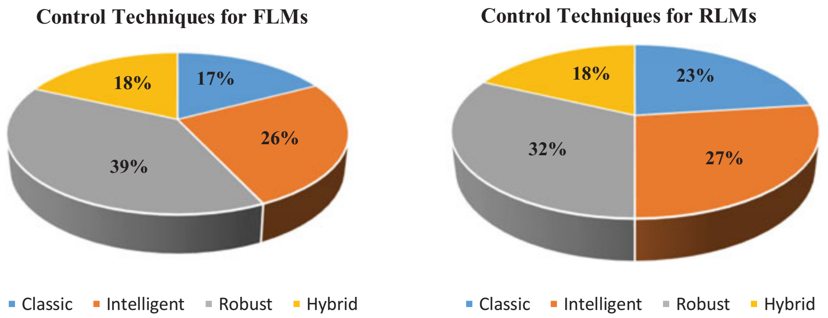

Fig. 7. Percentage of reported papers in this review article.

and a NN for motion control of a 2-DOF robot in a constrained workspace. The proposed FLC-NN controller has the ability to approximate the system nonlinearity which helps to generate a suitable compensatory control. A robust adaptive fuzzy controller has both robust controller and FLC, the robust controller is to deal with uncertainties and disturbances while the FLC is to estimate the error of the system position tracking as proposed in ref. [191] and verified via simulation work.

4. Extra Related Work

In order to review as much as possible of researches for control methods of FLMs and RLMs, many reported papers are categorized in Table I based on the type of manipulators and control techniques.

5. Summary

Figure 7 demonstrates the percentage of the reported papers in this review article which are recently published mostly since 2010, which covers journals and conferences; it is observed that the most papers of control techniques for FLMs are devoted in robust controllers with 39% and 32% for FLMs and RLMs respectively. The high percentage of utilizing robust controllers clarifies the importance of robust controllers in order to handle the nonlinear complexity of systems, deal with uncertainties of models, and reject external disturbances. The intelligent controllers come second with 26% for FLMs and 27% for RLMs. The lowest percentage of control methods for FLMs is the classic controllers, which means that they are not sufficient for controlling such complicated systems, but they are more used for RLMs since RLMs are easier to control than FLMs. Furthermore, the hybrid controllers have

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Table II. Advantages and disadvantages of control techniques.

Control type	Controller	Advantages and disadvantages	References
Classic	PD	Advantages 1. Easy to design 2. Can improve the system transient response Disadvantages 1. It does not improve the steady state error 2. It is not suitable to control FLMs 3. It is not able to deal with uncertainties 4. It is not robust to reject external disturbances	[118, 120]
	PID	Advantages 1. It has simple structure 2. It has stable performance 3. It can improve the transient response and the steady state error Disadvantages 1. It is required to retune the parameters for any change in the system properties 2. It is not capable to reduce the vibration of FLMs 3. It does not have the ability to deal with uncertainties and to reject external disturbances	[22, 23, 24, 100, 115]
	LQR	Advantages 1. It is easy for designing and structurally simple 2. It can be used for multivariable systems Disadvantages 1. It is not sufficient to suppress the vibration of FLMs 2. It cannot handle uncertainties 3. It is not robust enough to reject external disturbances	[26, 27, 234]
	LQG	Advantages 1. Its feedback gain and estimator can be designed separately 2. It can be used for multivariable systems	[29, 30, 235, 236]

Table II. Continued.

Control type	Controller	Advantages and disadvantages	References
		Disadvantages 1. It does not have enough capability to suppress the vibration of FLMs 2. Its performance is not satisfactory if there is uncertainty 3. Its robustness is not enough to reject external disturbances	
Intelligent	FLC	Advantages 1. It can handle nonlinear systems 2. It is easy for designing and implementation even by nonspecialists 3. It does not require accurate mathematical models of real systems Disadvantages 1. It is difficult of design for a complicated system with a large number of inputs 2. It may have unsatisfactory performance if uncertainties and external disturbances are existing	[40, 44, 45, 237, 47, 50]
	NN	Advantages 1. It is fast for designing a controller with lack of knowledge of system dynamics 2. It is a suitable method to avoid mathematical modeling issues Disadvantages 1. It cannot produce satisfactory performance for small network 2. It has computational complexity and time consuming issue for large network 3. It may have unsatisfactory performance in the presence of uncertainties and external disturbances	[39, 51, 52, 53]
Robust	SMC	Advantages 1. It can deal with uncertainties and nonlinear systems 2. It has the capability to reject external disturbances 3. It has stable performance even if the system has uncertainties and disturbances 4. It can reduce the vibration of FLMs Disadvantages 1. It has a serious chattering phenomenon which leads to inaccurate performance and energy loss	[64, 65, 66, 78]

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Table II. Continued.

Control type	**Controller**	**Advantages and disadvantages**	**References**
	H_∞	Advantages 1. It has high capability to handle uncertainties and nonlinear systems 2. It has high robustness for disturbance rejection 3. It can ensure high stability of performance 4. It is suitable for vibration suppression of FLMs Disadvantages 1. It has the limitation of designing and implementation complexity	[85, 89, 90]
	μ-synthesis	Advantages 1. It has high robustness to reject disturbances 2. It can guarantee high stability of performance for nonlinear systems and in the existence of uncertainties 3. It is able to suppress the vibration of FLMs Disadvantages 1. It is extremely complicated for designing and implementation	[101, 102, 177, 179]
Hybrid controllers		Advantages 1. They may have more than one advantage due to combining more than one controller and they may solve each other problems 2. They can ensure stable performance for complex systems in the existence of uncertainties and disturbances 3. They can control FLMs and reduce their vibrations Disadvantages 1. Combining more than one control technique leads to a complicated control structure	[103, 180, 181]

Table III. Comparison based on design, performance, and preferred application.

Control	Design	Performance		Application	
		Position tracking	Robustness to uncertainties	FLMs	RLMs
PD	Easy	Fast	Low		√
PID	Easy	Medium	Low		√
LQR	Easy	Fast	Medium	√	√
LQG	Easy	Fast	Medium	√	√
FLC	Medium	Medium	Medium	√	√
NN	Medium	Medium	Medium	√	√
SMC	Medium	Medium	Strong	√	
H_∞	Difficult	Fast	Strong	√	
μ-synthesis	Difficult	Fast	Strong	√	
Hybrid	Depends on integrated controllers	Depends on integrated controllers	Depends on integrated controllers	√	√

the lowest percentage of reported references in this article for controlling RLMs which indicates there is no highly demand for controlling RLMs by hybrid controllers as RLMs are easier for controlling than FLMs.

The advantages and disadvantages are summarized in Table II for the control techniques that are reviewed in this article. A detailed comparison for the aforementioned controller is tabulated in Table III. The table describes the difficulty of the controllers' design process and the controllers' performance based on position tracking and robustness to deal with uncertainties, and also indicates if a controller is suitable to control FLMs or RLMs.

6. Conclusion

The control techniques of classical controllers, intelligent controllers, hybrid controllers, and robust controllers such as SMC, H_∞ controller, and μ-synthesis controller are reviewed for FLMs and RLMs. The reported papers in this review reveal that the classical controllers are linear and easy for design and implementation, but they are not appropriate to suppress the vibrations of FLMs and to handle uncertainties of plants or to reject disturbances. Intelligent controllers have the ability to control nonlinear systems, estimate uncertainties, and reduce the effects of disturbances. However, FLC becomes complicated if a system has a large number of inputs and outputs. Furthermore, NNs require a large number of hidden layers for better performance which results in computational load.

Robust controllers based on SMC can handle nonlinear and complicated systems; such controllers have the ability to attenuate the vibrations caused by FLMs, deal with uncertainties, and are suitable to control RLMs as well. H_∞ and μ-synthesis as robust controllers are the most powerful controllers to deal with nonlinearities and uncertainties of systems and for vibration suppression of FLMs. However, SMC has a serious issue of chattering phenomenon which leads systems to an inaccurate performance. Furthermore, H_∞ controller and μ-synthesis controller are difficult to be designed and need long calculation process. Hybrid control techniques are used for controlling FLMs and RLMs as such techniques have the advantages of more than one control technique and can combine the advantages of linearity and nonlinearity. As a future contribution, combing FLC and LQR with a systematic optimization of parameters' tuning will develop a robust and suitable control algorithm for either FLMs or RLMs.

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