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REVIEW ARTICLE

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A systematic review of current and emergent manipulator control approaches

Abstract Pressing demands of productivity and accuracy in today's robotic applications have highlighted an urge to replace classical control strategies with their modern control counterparts. This recent trend is further justified by the fact that the robotic manipulators have complex nonlinear dynamic structure with uncertain parameters. Highlighting the authors' research achievements in the domain of manipulator design and control, this paper presents a systematic and comprehensive review of the state-of-the-art control techniques that find enormous potential in controlling manipulators to execute cutting-edge applications. In particular, three kinds of strategies, i.e., intelligent proportional-integral-derivative (PID) scheme, robust control and adaptation based approaches, are reviewed. Future trend in the subject area is commented. Open-source simulators to facilitate controller design are also tabulated. With a comprehensive list of references, it is anticipated that the review will act as a first-hand reference for researchers, engineers and industrial-interns to realize the control laws for multi-degree of freedom (DOF) manipulators.

Keywords robot control, robust and nonlinear control, adaptive control, intelligent control, industrial manipulators, robotic arm

1 Introduction

A robot, as defined by Robotic Industries Association, is "a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks". Robotics is a relatively new field of modern technology that crosses conventional engineering boundaries [1]. New domains of engineering (e.g., applications engineering, manufacturing engineering and knowledge engineering) are beginning to emerge to deal with the complexity of the discipline of robotics. It is predicted that within a few years, robotics engineering will stand on its own as a distinct engineering discipline [2]. Today, robots are being actively used in rehabilitation [3–5], motion assistance [6–8], haptics/VR [9], cognition [10,11] and target detection and tracking [12,13] in addition to space [14,15], nuclear power plants [16] and numerous other industrial applications [17,18].

Thanks to emerging research in mechatronics, robots are now playing a central role in industrial automation [19]. The increasing applications of robots in various industries arise from their characteristics of flexible programmability [20]. Robots are being deployed to accomplish tasks having strict requirements of accuracy, precision, repeatability, mass production and quality in addition to ease of human effort and cost effectiveness [21]. Typical example applications of robots in industry include welding, packaging, arranging, cutting, paint spraying, moving and sanding [22]. These tasks call for the deployment of manipulator-based robots in industry [23]. Task accomplishment is a consequence of movements of manipulator's joints in single/multiple direction(s) following a certain systematic pattern. In contrast with point-to-point robots, continuous path robots are the most advanced ones and require sophisticated computer controllers and softwares. The control variable(s) are mainly position, velocity, force/torque or a hybrid combination of all.

Research community reports few reviews on control strategies for robotic manipulators. However, many of these reviews (e.g., Refs. [24–26]) are either limited to the study of linear control strategy (e.g., Refs. [27,28]) or present an abstract discussion considering a specific application domain. In contrast, the present review, which is an extension of Ref. [29], is an in-depth study of linear, non-linear and adaptive control techniques that

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are applicable on robotic manipulators regardless of the application area. The comprehensive review of the state-of-the-art control techniques is beneficial to researchers and engineers to grasp the conceptual understanding of various control strategies and to help them in selecting the most appropriate control strategy as per their application requirements.

The remaining paper is organized as follows: Section 2 introduces fundamentals of a robotic manipulator while Section 3 discusses the recent advances; a survey of reported software packages for the simulation of manipulator control is presented in Section 4; finally, Section 5 gives conclusions.

2 Robotic manipulator

Manipulator is a mechanical structure of the robot although scientific literature usually uses the two words 'robot' and 'manipulator' interchangeably [30]. Comprising links with rotary or translational joints, which are normally connected in series scheme, a manipulator has three parts: Arm, wrist and hand. The function of arm is to place an object in a certain location in 3D Cartesian space while the wrist orients it. The hand, also referred as an end-effector or tool, is used for object manipulation.

The primary advantage of a serial manipulator is its large operational workspace [31] with respect to the size of the manipulator and the floor space occupied by it. A typical 6-degree of freedom (6-DOF) serial robotic manipulator for the simulation of industrial applications was reported in Ref. [32]. Illustrated in Fig. 1, the manipulator, together with various other system components, has been later on presented and marketed as AUTanomous Articulated Robotic Educational Platform (AUTAREP) [33]. The novelty of the platform lies in its open-source software and hardware architectures, wide range of sensory capabilities and pseudo-industrial nature. Based on the design library having more than 100 kernel commands, the platform can be used to test and validate advanced control algorithms and trajectory tracking strategies.

Design of a controller for a manipulator is a complex task. Initially, the user's requirements are identified. In a broader perspective, these requirements, given by a client, manufacturer, seller or end-user, become the starting point of the conceptual design [34]. The control designer or roboticist then translates the layman requirements into technical engineering specifications based on which the manipulator parameters including number of joints, number of DOF, mechanism type, actuation, transmission and sensing modules are selected. This is followed by the robot modeling which involves derivation of kinematics and dynamics. Kinematics can be formulated based on Denavit-Hartenberg parameters, screw theory, Hayati-Roberts representation, Lie Algebra or geometrical method. A review of these formula was presented by Ajwad et al. [35]. The robot dynamics can be derived using Newton-Euler or Lagrange formulation [36]. Lagrange requires computation of kinetic and potential energies. The general dynamic model [37] for n-serial link robotic manipulator with revolute joints is given by Eq. (1).

$$\boldsymbol{M}(\boldsymbol{q},\dot{\boldsymbol{q}})\cdot\ddot{\boldsymbol{q}} + \boldsymbol{V}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau} - \boldsymbol{\tau}_f, \quad (1)$$

where $\boldsymbol{M}(\boldsymbol{q}) \in \boldsymbol{R}^{n\times n}$ is the inertia matrix, vector $\boldsymbol{V}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \boldsymbol{R}^n$ represents the centrifugal and coriolis forces, vector $\boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{R}^n$ indicates the gravitational force effect, $\boldsymbol{\tau} \in \boldsymbol{R}^n$ is the applied torque vector to the robot's joints, $\boldsymbol{\tau}_f \in \boldsymbol{R}^n$ is the frictional forces/torques vector, and $\boldsymbol{q} \in \boldsymbol{R}^n$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ are the vectors for angular position, velocity and acceleration,

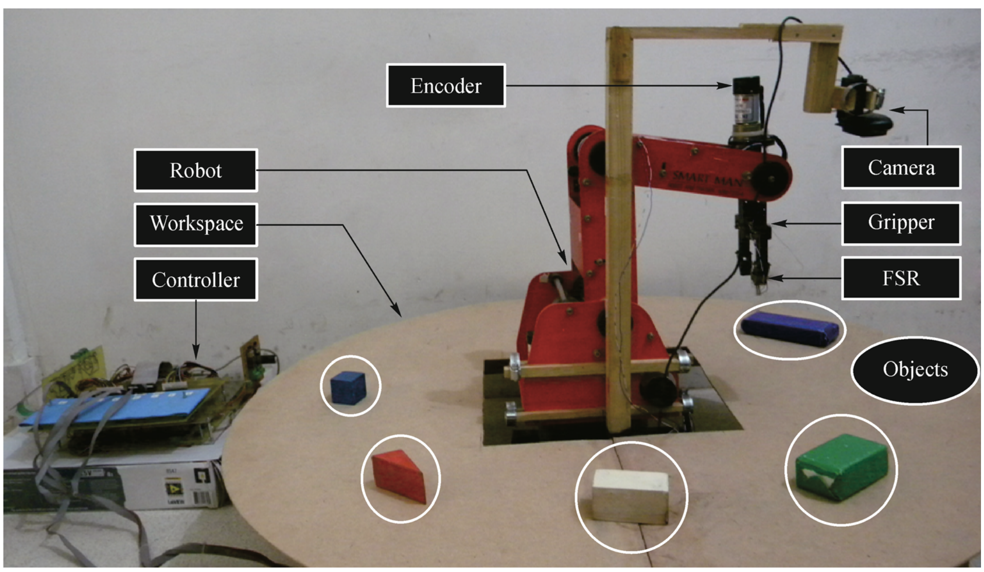

Fig. 1 AUTAREP realized by researchers at COMSATS Institute, Pakistan [33]

respectively.

As an example of derivation of models of a multi-DOF manipulator, reader is strongly encouraged to see Refs. [38] and [33] which respectively present the kinematics and dynamics of the AUTAREP manipulator. Having modeled a manipulator, the control law can then be derived to achieve required performance. Finally, depending upon the application scenario, the designed controller is physically realized using programmable logic controller, embedded controller, digital signal processor, field programmable gate array or discrete electronic components [39]. The overall sequential procedure is highlighted in Fig. 2.

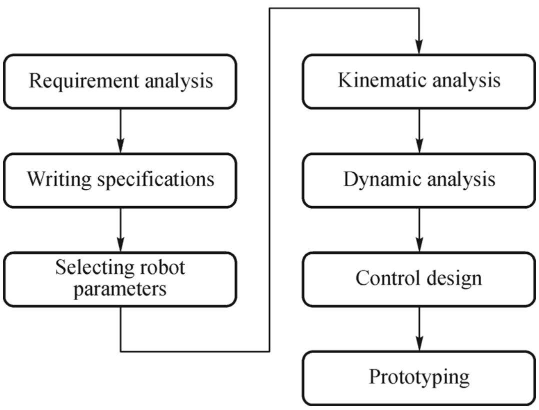

Fig. 2 Manipulator control design — Sequential engineering approach

3 Recent advances

Recent advances in manipulator control can be commented by categorizing the strategies into three sub-domains: Intelligent PID control, robust control and adaptive control.

3.1 Intelligent PID control

Most often, in today's applications, the simple PID control is modified to improve the speed of recovery from commonly encountered process saturation scenarios [25]. The modification in PID control can be done by changing parameters, improving measurements or cascading multiple controllers [40,41]. The advancements in PID control are in two folds: Improvements in tuning methods and trend to combine PID with modern control techniques and other algorithms.

Literature reported various methods to tune PID controllers [24], including Ziegler-Nichols open/closed loop, Lambda tuning, Cohen-Coon, integral of time weighted absolute error (ITAE)-load, etc. Recent research highlights tuning using model switching adaptation and other approaches based on particle swarm optimization (PSO), genetic algorithm (GA), ant colony optimization (ACO) and evolutionary programming (EP). The tuning methods have been well reviewed in the literature. A comparative study of these methods has already been done in Refs. [42–44].

Combining PID or its modifications with robust, nonlinear and adaptive control approaches is another milestone, on which researchers are currently working. This tendency is further elaborated in the following sections. Another recent trend is to combine PID with other application of specific algorithms to achieve optimum performance. For example, Iqbal et al. [45] proposed a novel rehabilitation device for the hand, where the exoskeleton, consisting of serial link manipulator-type fingers, is controlled (Fig. 3) by PID combined with minimum jerk trajectory generation algorithm [46]. After limiting the overall coefficients, the power driver drives the exoskeleton motors. The driver has two interrupts: One for over-current protection (I_sense) and other for emergency stop initiated by the operator. The motor encoder data are sent as feedback to close the control loop.

Considering AUTAREP, Ref. [47] reports a novel control scheme based on PID. A practical application of pick and place task during objects sorting has been exemplified. The trajectories followed by various joints of the robot during this task are shown in Fig. 4. The task accomplishment has been divided into time intervals (T1 to T5) according to the manipulator's activity. These intervals are defined as: T1: Moving to pick the object; T2: Gripper closed (object picked-up); T3: Moving towards destination position; T4: Gripper open (object dropped); T5: Moving towards home position.

3.2 Robust and non-linear control

The primary limitation of PID control is its nature of being a constant gain feedback system without having direct knowledge of the plant thus compromising the overall performance. Also, the linear and symmetric behavior of PID control law deteriorates the performance in case of controlling the industrial robots, since the processes in industry exhibit nonlinear process dynamics, unmeasured disturbances, resolution and sensitivity limits, measurement delay and lag, component non-idealities and nonlinearities, and so on. Practical implementation of the inverse dynamic law requires that not only the parameters in the dynamic model of the system be known precisely, but also the complete equations of motion be computable in real-time, typically 60–100 Hz [2]. However, these requirements are difficult to satisfy in practice. Real world systems exhibit nonlinear behavior by nature and have uncertain parameters. This can be due to inexact cancellation of the nonlinearities in the system or computational round off. Classical control techniques may not give optimum response and thus highlight the need of sophisticated control laws to ensure robustness. Robust

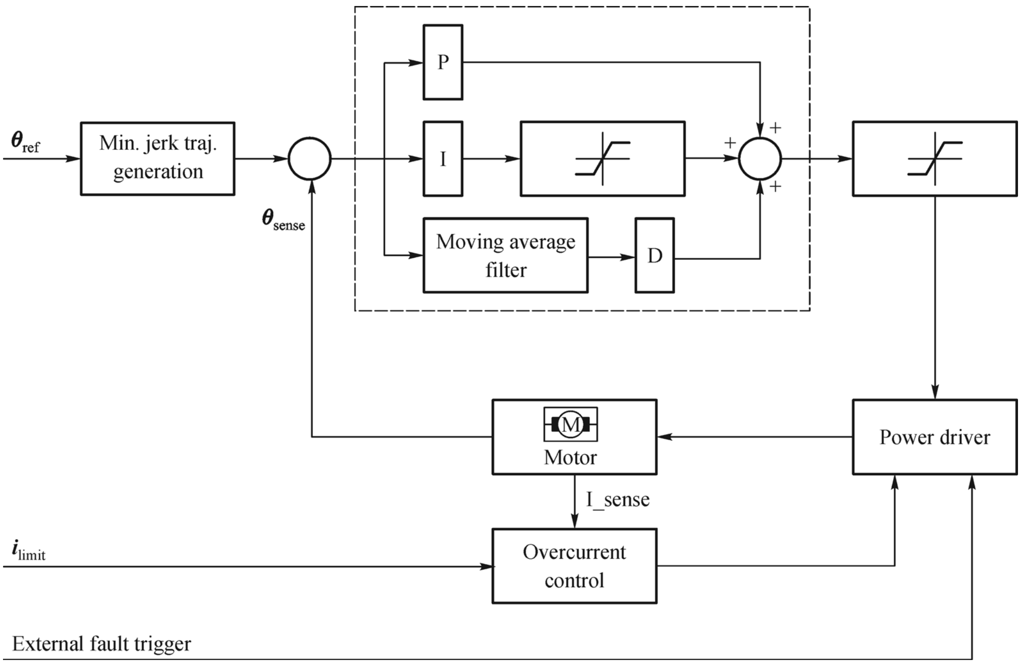

Fig. 3 Control architecture of the manipulator-type exoskeleton rehabilitation system [46]

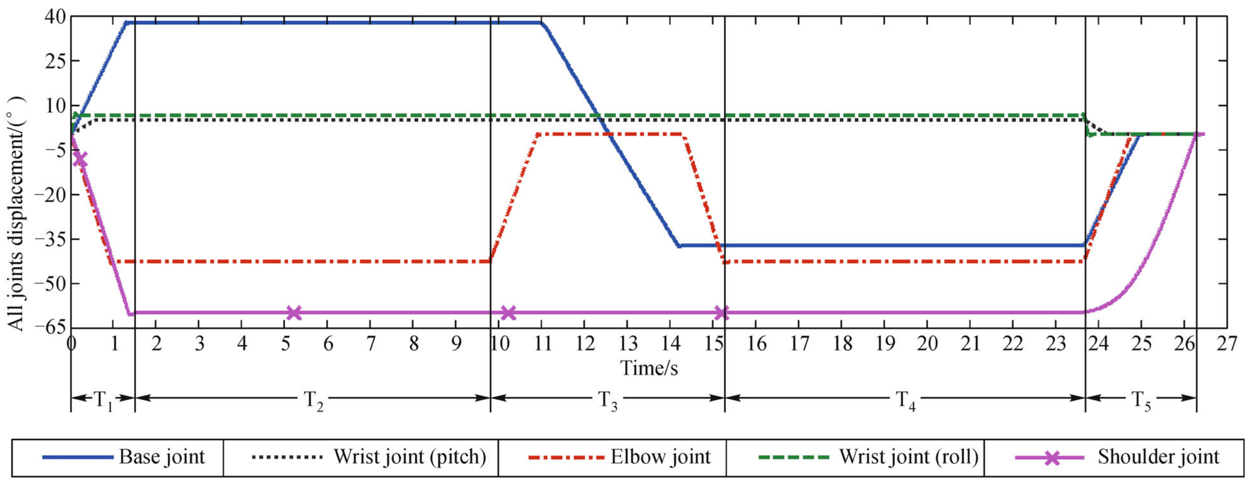

Fig. 4 Encoder data of AUTAREP joints for pick & place task [47]

controllers are fixed structures that guarantee stability and performance in bounded uncertainties. These control strategies include computed torque control (CTC), sliding mode control (SMC), model predictive control (MPC), H_∞ control, disturbance observer based controller (DOBC), passivity based controller (PBC), etc.

CTC, a special case of feedback linearization [41], is often combined with PID or its variants. Its major advantages include high tracking accuracy, lower energy consumption and lower feedback gains. Block diagram of CTC with proportional derivative (PD) controller is shown in Fig. 5.

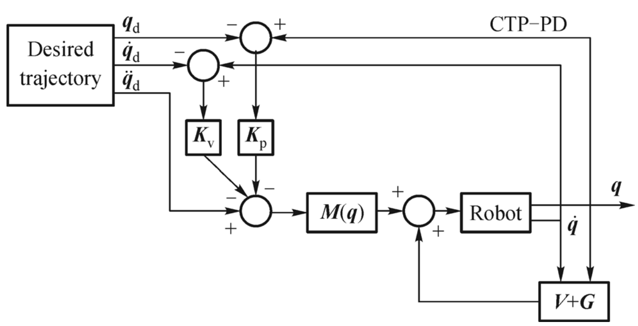

Fig. 5 Block diagram of CTC-PD for tracking joint angle of a robot [48]

The corresponding control law for tracking an n-DOF robotic arm is given by

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q},\dot{\boldsymbol{q}})\cdot\left(\ddot{\boldsymbol{q}}_{\mathrm{d}} - \boldsymbol{K}_{\mathrm{v}}\cdot\dot{\boldsymbol{e}} - \boldsymbol{K}_{\mathrm{p}}\cdot\boldsymbol{e}\right) + \boldsymbol{V}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}), \quad (2)$$

where $\ddot{\boldsymbol{q}}_{\mathrm{d}} \in \boldsymbol{R}^n$ is the second derivative of the desired joint angle vector ($\boldsymbol{q}_{\mathrm{d}}$), $\dot{\boldsymbol{e}} \in \boldsymbol{R}^n$ is the derivative of the error signal, $\boldsymbol{K}_{\mathrm{p}} \in \boldsymbol{R}^{n\times n}$ and $\boldsymbol{K}_{\mathrm{v}} \in \boldsymbol{R}^{n\times n}$ are the constant gain matrices associated with proportional and derivative terms, respectively.

Considering AUTAREP manipulator, Ullah et al. [49] simulated CTC-PD to demonstrate the efficacy of this approach for trajectory tracking. Figure 6 presents the ramp responses for various values gains λ. Other notable research on CTC was reported in Refs. [50–52].

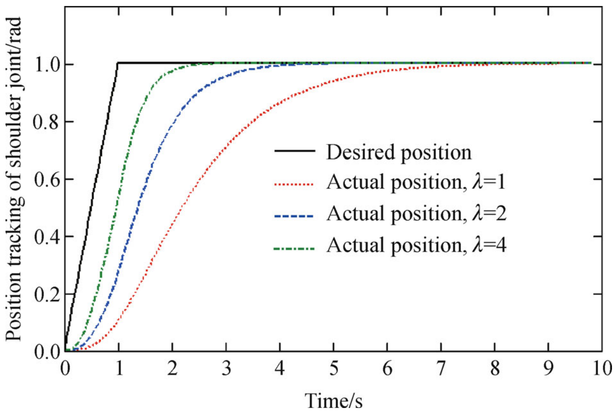

Fig. 6 Tracking using CTC-PD corresponding to various λ values: Ramp responses [49]

Another robust approach, SMC, is inherently designed to eliminate uncertainties and disturbances. In a controller based on SMC, the most important task is the switching control which drives the plant states to the selected switching surface and keeps it there for all future times [53]. To characterize this task, a Lyapunov function is defined for state variables which must remain positive and will become zero only when state variables are zero. System states variables approach zero in finite time when this function's derivate is negative [54]. For a manipulator with n joints, the sliding manifold $\boldsymbol{S}=[s_1, s_2, ..., s_n]^{\mathrm{T}}$ is typically designed as

$$\boldsymbol{S} = \boldsymbol{C}\cdot\boldsymbol{e} + \dot{\boldsymbol{e}}, \quad (3)$$

where $\boldsymbol{C} \in \boldsymbol{R}^{n\times n}$ is a diagonal matrix which must satisfy the Hurwitz condition, i.e., its all entries must be positive. SMC consists of two parts: Equivalent control and robust control. The first part ensures that states of the closed-loop system follow the sliding manifold surface. This control, given in Eq. (4), can be computed by differentiating Eq. (3) w.r.t. time, setting $\boldsymbol{S} = 0$ and then using Eq. (1).

$$\boldsymbol{\tau}_{\mathrm{eq}} = \boldsymbol{M}(\boldsymbol{q},\dot{\boldsymbol{q}})\cdot(\ddot{\boldsymbol{q}}_{\mathrm{d}} - \boldsymbol{C}\cdot\dot{\boldsymbol{e}}) + \boldsymbol{V}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}). \quad (4)$$

A discontinuous function of sliding manifold is required to compensate the dynamic model uncertainties. A good candidate is given by

$$\boldsymbol{\tau}_{\mathrm{disc}} = -\boldsymbol{K}\cdot\mathrm{sgn}(\boldsymbol{S}) = -\boldsymbol{K}\cdot\mathrm{sgn}(\boldsymbol{C}\cdot\boldsymbol{e} + \dot{\boldsymbol{e}}), \quad (5)$$

where $\boldsymbol{K} \in \boldsymbol{R}^{n\times n}$ is the discontinuity gain matrix and the "sgn" function returns a vector with the sign of the components of $\boldsymbol{S}(\ )$. A typical SMC Lyapunov function, defined as $L = 0.5S^2$, restricts to be positive definite.

Considering AUTAREP manipulator, a performance comparison between CTC and SMC is presented in Ref. [55]. It proved that the later approach outperformed both in terms of trajectory tracking and disturbance rejection. Given bounded matched disturbance, Fig. 7 illustrates step responses corresponding to the two control techniques. Other prominent SMC implementations were reported in Refs. [56–60].

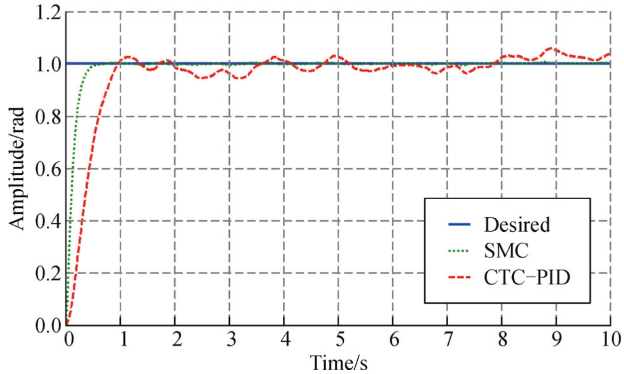

Fig. 7 Comparative tacking performance in the presence of disturbances: Step responses of SMC and CTC [49]

MPC offers an intuitive solution of control problems where the conventional algorithms utilize pre-computed state or output feedback control law. MPC has capability to control manipulator even in the presence of constraints [61]. The working principle of discrete time MPC is illustrated in Fig. 8. An optimization problem is constructed to minimize the error between set point and predicted output subject to control horizon and perdition horizon for a sampling instant.

Considering a second order linear plant, the incremental optimal control law for a discrete time MPC [62] can be written as

$$\begin{aligned} \boldsymbol{u}_c(k) &= \textstyle\sum_1^k \Delta\boldsymbol{u}(k_i), \\ \Delta\boldsymbol{u}(k_i) &= \boldsymbol{K}_y\boldsymbol{r}(k_i) - \boldsymbol{K}_{\mathrm{mpc}}\boldsymbol{x}(k_i), \end{aligned} \quad (6)$$

where $\boldsymbol{r}(k_i)$ represents set point information and $\boldsymbol{X}(k_i)$ is state of the augmented plant at a sampling instant k_i and is

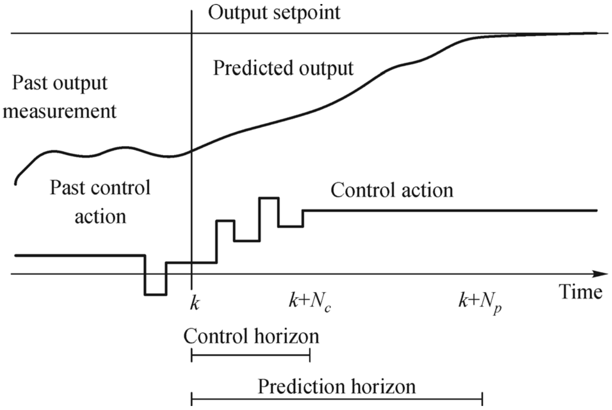

Fig. 8 Waveform illustrating working principle of discrete time MPC

defined as $\boldsymbol{X}(k_i) = [\,\Delta\boldsymbol{x}(k_i) \quad \Delta\dot{\boldsymbol{x}}(k_i) \quad \boldsymbol{x}(k_i)\,]^{\mathrm{T}}$. $\boldsymbol{K}_y \in \boldsymbol{R}^{n\times n}$ and $\boldsymbol{K}_{\mathrm{mpc}} \in \boldsymbol{R}^{n\times 3n}$ are obtained by solving the optimization problem such that the error function between the set point and predicted output is minimum. A typical MPC law for a robotic arm takes the form of

$$\boldsymbol{\tau}(k) = \boldsymbol{M}(\boldsymbol{q},\dot{\boldsymbol{q}})\cdot\{\boldsymbol{u}_c(k)-\dot{\boldsymbol{q}}(k)-\boldsymbol{q}(k)\} + \boldsymbol{V}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}), \tag{7}$$

where $\boldsymbol{u}_c$ is the auxiliary control signal and calculated using MPC considering the states as $\boldsymbol{X}(k_i) = [\,\Delta\boldsymbol{q}(k_i) \quad \Delta\dot{\boldsymbol{q}}(k_i) \quad \boldsymbol{q}(k_i)\,]^{\mathrm{T}}$. Overall MPC law can be written as

$$\boldsymbol{\tau}(k) = \boldsymbol{M}\Big(-\dot{\boldsymbol{q}}(k)-\boldsymbol{q}(k) + \sum\nolimits_1^k\{\boldsymbol{K}_y\boldsymbol{r}(k_i)\boldsymbol{K}_{\mathrm{mpc}}\cdot\boldsymbol{X}(k_i)\} + \boldsymbol{V} + \boldsymbol{G}\Big). \tag{8}$$

The parameters of a real system vary with time, which results in deterioration of the controller performance. MPC implementation for robotic manipulators was reported in Refs. [63–67].

H_∞ being a robust control technique is based on solution of a mathematical optimization problem due to the presence of uncertainties in a plant's behavior. For this purpose, H_∞ control is designed to minimize the closed loop effects of perturbations [68]. Interested readers are referred to Refs. [69–71] for H_∞ implementation. The last two strategies DOBC and PBC are comparatively discussed in detail in Ref. [29] with the corresponding implementations reported in Refs. [72–79] and [80–85], respectively.

3.3 Adaptive control

The main advantage of adaptive control techniques is that the controller changes its parameters to compensate time varying behavior of the system [86]. A direct adaptive control approach, wherein the estimated parameters are directly used in the adaptive controller, was first implemented in 1958 [87,88]. The indirect adaptive approach, in which the estimated parameters are used to determine the control law, was significantly developed starting with the research of Åström and Wittenmark [89]. In robotics, initial research was carried out in Ref. [90] to estimate the unknown manipulator and payload parameters. Since then, the focus of adaptive control was on identification of unknown parameters [87,91–93] and model based compensation of nonlinearities in the robotic manipulators [94]. Figure 9 illustrates the basic concept of adaptive controller which is categorized as model reference adaptive control (MRAC).

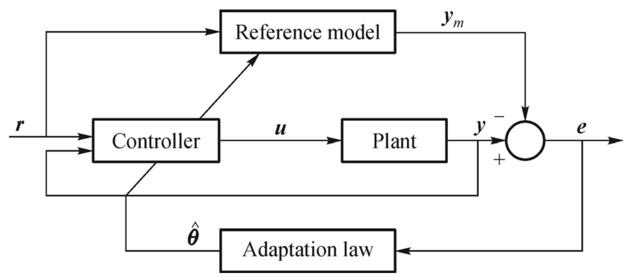

Fig. 9 Block diagram illustrating MRAC

Considering the generalized dynamic model for n-link serial robotic manipulator given in Eq. (1), various adaptive controllers with direct and indirect approaches have been proposed. Two of them will be discussed here. The neural network (NN) based control design combined with a robust control technique, such as SMC, is given as

$$\boldsymbol{\tau} = -\boldsymbol{K}\cdot\mathrm{sgn}(\boldsymbol{S}) + \boldsymbol{u}_{\mathrm{NN}} + \boldsymbol{u}_{\mathrm{a}}, \tag{9}$$

where $\boldsymbol{u}_{\mathrm{NN}}$ and $\boldsymbol{u}_{\mathrm{a}}$ are the control inputs obtained from NN approximation and parameter adaption respectively and are given by

$$\boldsymbol{u}_{\mathrm{NN}} = \boldsymbol{\omega}\phi,\ \boldsymbol{u}_{\mathrm{a}} = \frac{\boldsymbol{S}}{\|\boldsymbol{S}\|+\mu}\alpha, \tag{10}$$

where $\boldsymbol{\omega} \in \boldsymbol{R}^n$ and ϕ are the output weight and the basic function of the NN technique respectively, μ is a positive constant, α is the adaptive term and its dynamics is given by

$$\dot{\alpha} = \frac{\|\boldsymbol{S}\|^2}{\|\boldsymbol{S}\|+\mu}. \tag{11}$$

The block diagram describing the adaptive neural network based SMC of a robotic manipulator is shown in Fig. 10.

Fuzzy adaptive controllers due to their design simplicity are gaining a lot of attention of the researchers. In robotics,

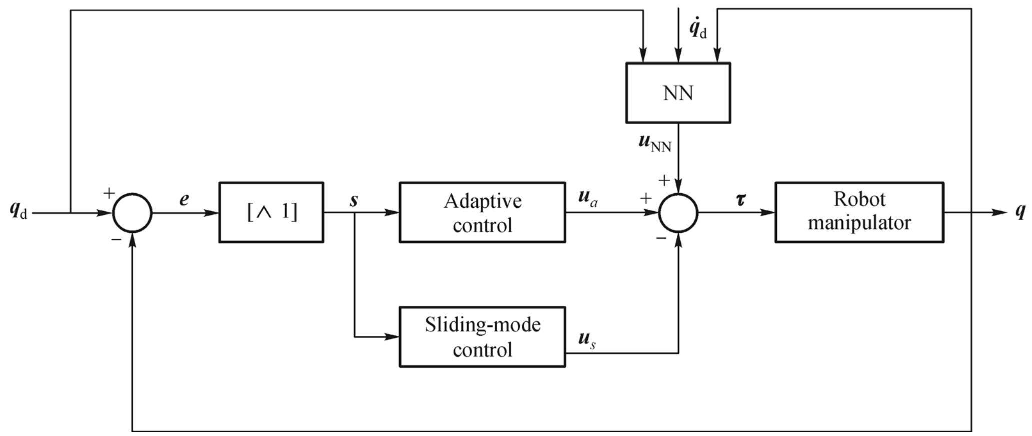

Fig. 10 Block diagram of adaptive neural network based sliding mode control (NNSMC) control [87]

fuzzy control is implemented for unknown parameters estimation and to compensate nonlinearities in the manipulator [93]. Figure 11 shows adaptive control technique with sliding mode and fuzzy logic.

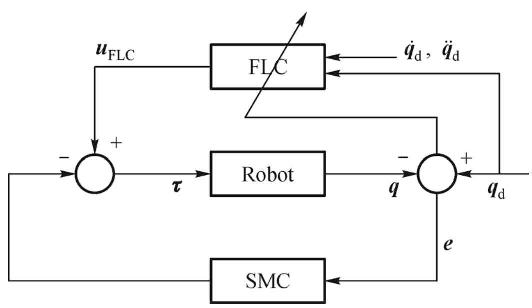

Fig. 11 Block diagram of adaptive Fuzzy logic control

Considering the dynamics of robot manipulator given in Eq. (1), the control law can be represented as

$$\boldsymbol{\tau} = -\boldsymbol{K}\cdot\operatorname{sgn}(\boldsymbol{S}) + \boldsymbol{u}_{\mathrm{FLC}}. \tag{12}$$

The nonlinear adaptive control input to compensate nonlinearities, torque disturbances and payload variation is considered as

$$\boldsymbol{u}_{\mathrm{FLC}} = \boldsymbol{\beta}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\cdot\boldsymbol{\theta}, \tag{13}$$

with $\boldsymbol{\beta} \in \boldsymbol{R}^{n\times n}$ and updating law $\boldsymbol{\theta} \in \boldsymbol{R}^{n}$, the robot system is locally asymptotically stable. The adaptive parameter is given by

$$\dot{\boldsymbol{\theta}} = -\boldsymbol{\Gamma}\cdot\phi\cdot\boldsymbol{S}^{\mathrm{T}} - k_w\boldsymbol{\Gamma}\cdot\|\boldsymbol{S}\|\cdot\boldsymbol{\theta} \tag{14}$$

where k_w and ϕ are positive constants and $\boldsymbol{\Gamma} \in \boldsymbol{R}^{n\times n}$ is a positive definite matrix.

In the recent research, it has been proven that classical control techniques loss their effectiveness in presence of nonlinearities such as friction, aging and varying environmental conditions. There are two ways to cater for unknown disturbances. One way to compensate the nonlinear behavior of a system is to obtain its precise model which considers all the nonlinearities present in a system. However, it is impossible to obtain an exact model of a system. Therefore, researchers in the control field are focusing on robust and adaptive control techniques. The robust techniques, however, require a priori knowledge of system parameters. For complex systems where model based control implementation is difficult, adaptive control techniques could be considered [90]. It is worth mentioning here that a controller can give an improved performance if both robust and adaptive control techniques are implemented [87].

4 Virtual tools for control simulation

The benefits offered by following a computer based approach instead of using formula based methods to design control were reviewed in Ref. [95]. Virtual robotic systems, offering illustrative and cost-effective solution, have potential in explaining robotic concepts in a simple but effective way. These tools generally exploit the integration of engineering software (usually Matlab/C ++) and a graphical tool (e.g., virtual reality modelling language) to permit acquisition of fascinating pictures or animations of a robotic manipulator. Most of the recent tools offer a user-friendly graphical user interface (GUI) for interaction with the computer rather than mind-numbing keyboard commands. A typical example is illustrated in Fig. 12. Other advantages of virtual platforms include working flexibility, ease in changing simulation parameters/environment and possibility of collaborations among multiple students/research groups.

Scientific community reports various virtual robotic applications to enhance the understanding of system dynamics and to simulate response of the control system. Over the years, MATLAB has emerged as a very popular, intuitive and easy visualization and simulation platform for

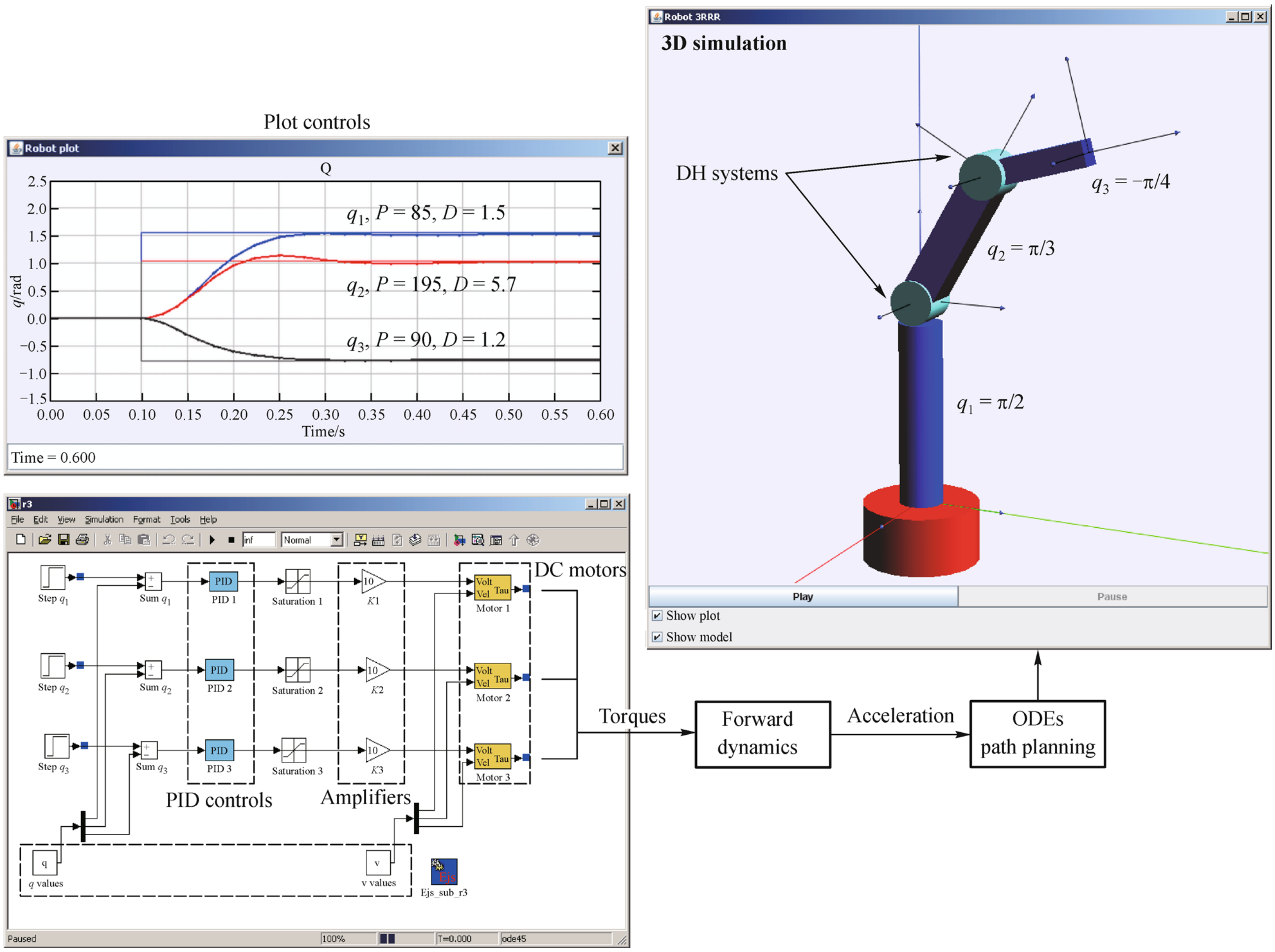

Fig. 12 Interface for position control of a manipulator with 3 rotational DOF [96]

demonstrating robotic concepts. Other prominent examples of platforms that have potential in training and simulating control systems include robotics toolbox for MATLAB [97,98], Roboticad [99], EJS + EjsRL [96], planar manipulator toolbox [100], HEMERO [101], ROBOTLAB [102], Robotica [103], TUM platform [104], V-REP (virtual robot experimentation platform) [105], DUT platform [106], ReDySim [107], RobLib [108], Arm6x [109], ROBOSIM2 [110], etc. The comparative review of these platforms is presented in Table 1.

5 Conclusions

Presented in the paper are control advancements that have significantly improved manipulator's functionality. The choice of a particular control strategy together with its implementation manner can considerably impact a manipulator's performance and accordingly its applications range. The software-hardware trade-off between the programming/architecture of the controller and the mechanical structure of the system needs to be properly addressed by a control designer.

It is a myth that the area of manipulator control is already saturated. Sophisticated control algorithms together with fusion of sensors and learning capabilities will offer intuitive and user-friendly installation, maintenance and programming of industrial manipulators. The productivity can be further increased by employing hybrid vision and force based control schemes. Based on the presented discussion, it seems very probable that in the very near future, PID control gets smarter and will continue to be the main workhorse of industry while in the far future, computationally inexpensive hybrid non-linear and adaptive control approaches provide adequate performance to meet high demands of precision, accuracy, flexibility, repeatability, maintainability, operability, reliability, safety and profitability. The innovative use of the developing and expanding capability of the non-linear approaches is the key to the future of robotic manipulator.

This review is anticipated to boost cutting-edge research in the domain of 'robot control'. Results of this study can

Table 1 Comparative review of reported platforms for simulating control systems for manipulators

Framework	Developed by	Environment	GUI	Traj. Planning	Robots in library	Dynamic algo.	Ref.
EJS + EjsRL	Univ. of Alicate, Spain	Java	•	•	Multiplatform support	Newton-Euler	[96]
CorkeToolBox	CSIRO, Australia	MATLAB	Limited	•	Serial manipulators	Newton-Euler	[97]
RobotiCad	Univ. of Bologna, Italy	MATLAB	•	•	Cartesian and serial robots	Newton-Euler / Lagrange	[99]
Planar Manipulator Toolbox	Inst. Jožef Stefan, Slovenia	MATLAB/ Simulink	Limited	•	Planar manipulators (n revolute joints)	Lagrange	[100]
HEMERO	Univ. of Seville, Spain	MATLAB		•	PUMA 560	Newton-Euler	[101]
ROBOTLAB	Federal Univ. of Paraíba, Brazil	MATLAB		•		Newton-Euler	[102]
Robotica	UIUC, USA	Mathematica, Simnon, C	•		None	Lagrange	[103]
TUM Platform	Tech. Univ. Munich, Germany	MATLAB	•				[104]
V-REP	Coppelia Robotics, Germany	Windows, MacOSX and Linux	•	•	Generic	ODE, Bullet, Vortex	[105]
DUT Platform	Delft Univ. of Tech., Netherland	MATLAB	•		16 robots each with 6 DOF		[106]
ReDySim	Indian Institute of Technology (IIT), Delhi	MATLAB	•	•		DeNOC based on Newton-Euler	[107]
RobLib	Inst. of Engineering of Coimbra, Portugal	Borland Delphi	•	•	RP, RR	Newton-Euler	[108]
Arm6x	Concurrent Dynamics International	MATLAB			None	Newton-Euler / Lagrange	[109]
ROBOSIM2	Thammasat Univ., Thailand	MATLAB, LISP	Limited		R, RR, P, PP, RP, PR		[110]

be directly mapped to the selection of appropriate control strategy corresponding to specific requirements. Once the control strategy is decided, the mentioned recent findings and up-to-date references corresponding to the selected technique are expected to significantly facilitate the research. This up-to-date review may also serve as a worthy resource for the researchers developing virtual platforms for simulating manipulator control.

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