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A survey on Intelligent control schemes in two-link flexible manipulators

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Abstract - The studies on TLFMs are classified into three main categories as modeling methods, dynamical analyses, and control techniques. Flexible manipulators are considered because of their several advantages over rigid manipulators. Moreover, Two-link flexible manipulators are more used in comparison with other types of flexible manipulators. Different kinds of control problems exist for a two-link flexible manipulator, which includes position control, tip position control, trajectory tracking, tip position trajectory tracking, vibration control, force control, motion control, and a hybrid of the above-mentioned control problems. In this paper, a comprehensive review of intelligent control schemes is presented on two-link flexible manipulators (TLFMs). In this regard, fuzzy logic control-based schemes, Genetic algorithm-based schemes, and Artificial neural network (ANN)-based schemes on TLFMs are reviewed.

Keywords: Flexible manipulators, Intelligent control, fuzzy logic control, Genetic algorithm, Artificial neural network (ANN)

1. Introduction

In order to build modern robotic manipulators to satisfy the needs of industrial applications, it is important to ensure by decrease the weight of the link manipulators and utilizing flexible materials to satisfy the special needs of industries. Significant control problems appear in flexible link manipulators such as vibration, and static deflection from external effects, and design errors. These factors can decrease the end effector accuracy, increase settling time, and complicate the controller design scheme. Currently, flexible link manipulators have been designed and have the following advantages: (i) greater ratio of payload weight to robot weight, (ii) use of less powerful actuators which reduces the energy consumption, (iii) cheaper construction, (iv) faster motion, (v) safe operation [1-2].

Robotic manipulators are highly demanded to work in dangerous, routine, and difficult jobs instead of humans in order to achieve accurate, faster, and economical operations [3].

Manipulators are divided into rigid manipulators and flexible manipulators (FM). In this paper, FMs are considered because of their several advantages over rigid manipulators. Some important advantages of the FMs can be listed as low energy consumption, smaller size, economical, lightweight, more workspace, and portability [4]. However, the limitations of flexible manipulators are control complexity, uncertainties, and MIMO and nonlinear systems. The main reasons for the aforementioned complexities are the choice of dynamical model, required structure, and operation of FMs.

The studies on TLFMs are classified into three main categories as modeling methods, dynamical analyses, and control techniques [5]. Different kinds of control problems exist for a two-link flexible manipulator, which includes position control, tip position control, trajectory tracking, tip position trajectory tracking, vibration control, force control, motion control, and hybrid of the above-mentioned control problems.

In this paper, intelligent control schemes applied to TLFMs are presented as fuzzy logic control-based schemes, Genetic algorithm-based schemes, and Artificial neural network (ANN)-based schemes. In fuzzy logic, control-based schemes, Fuzzy and SMC, fuzzy PD, and fractional order fuzzy PD, Fuzzy Neural Network Control, FLC and Feedback, FLC and Adaptive are presented. In Genetic algorithm-based schemes, GA and SMC, GA and PD, GA and fuzzy, and GA-optimized feedback and adaptive control are reviewed. In Artificial neural network (ANN)-based schemes, Conventional NN, NN and PID control, ANN and LQR, ANN and H∞ control, ANN and adaptive control, ANN and feedback linearization control, Neuro-SMC, STC using ANN and PI controller, ANN and Computed torque control using visual sensor, Weighted Multiple Neural Network Boundary Control, self-tuning strain feedback gain controller Using ANN, learning control of FLM using neural networks, diagonal recurrent neural network control technique, and Neural Network Control Using Assumed Mode Method are reviewed.

2. Intelligent control

Sometimes model of a real process is not known accurately or is difficult to formulate properly. So, due to the lack of an accurate model, the design of a control system is difficult. This problem can be overcome by incorporating linguistic information from human experts. Fuzzy logic control, artificial neural network, genetic algorithm, etc. are the types of intelligent control techniques.

2. 1. Fuzzy logic control

A conventional control may not work satisfactorily when the dynamics of the manipulator is not known accurately or if dynamics varies in different operating conditions. However, designers can handle such complexity based on their experiences. Thus, a controller is required to design based on the linguistic information from the human experiences. Ease in design and implementation without the knowledge of the accurate model are the main advantages of a fuzzy logic controller [6]. It is a non-modeled based control technique. The general structure of a FLC consists of four components (i) rule base, (ii) inference mechanism, (iii) fuzzification inference, (iv) defuzzification inference. In this structure, e and $\dot{e}$ variables of the flexible manipulator can be used as input to the fuzzy controller.

In [7] a fuzzy logic controller of a TLFM is presented. The model of the manipulator is separated into two parts using singular perturbation technique. Separate fuzzy logic controllers are designed for slow and fast dynamics for tracking control and deflection suppression of the manipulator, respectively. The results are verified using simulation and experiment. Tip position control and vibration suppression of a TLFM are presented in [8] using FLC. The control technique is termed as Fuzzy model reference learning controller. The FLC is designed in two forms direct FLC and coupled FLC. The results are presented using numerical simulation and experiment. The performance of the controller is evaluated in the presence of payload variation.

2. 1. 1. Fuzzy and SMC

Hybrid control scheme is in [9] for trajectory tracking control and vibration suppression of a TLFM. A PID control is used for trajectory tracking and a SMC is used for vibration suppression of the manipulator. Fuzzy logic is used along with the PID for trajectory tracking control. Numerical simulations are performed for the results.

Fuzzy terminal sliding mode control is introduced in [10] for position control of a TLFM. The dynamics of the manipulator are divided into two parts using two-time scale property. Fuzzy SMC is used for controlling slow subsystems. LQR and reduced order observer are used for controlling the fast subsystem. AMM is used for modeling the dynamics of the flexible manipulator.

2. 1. 2. fuzzy PD, and fractional order fuzzy PD

In [11] PD, fuzzy PD, and fractional order fuzzy PD controllers are compared in terms of trajectory tracking, vibration suppression, robustness against disturbances, and energy consumption to control the rigidflexible two-link manipulator. They highlighted that the fractional order fuzzy PD controller performed better than other controllers.

2. 1. 3. Fuzzy Neural Network Control

In [12] fuzzy neural network control is studied for trajectory tracking and vibration suppression of single-link flexible manipulator and compared the control performance of the proposed technique with the PD control.

In [13] experimental studies on active vibration control of a two-link flexible manipulator is studied by employing three control algorithms: generalized minimum variance self-tuning control, Takagi-Sugeno model-based fuzzy neural network control, and PD control. Furthermore, they evaluated the effectiveness of the first two controllers as compared to that of the PD control in terms of vibration suppression.

Hybrid neuro-fuzzy tracking control of a TLFM is presented in [28]. The primary loop of the proposed controller contains FLC and neural network in the secondary loop for compensating the coupling effect between rigid and flexible motion along the interlink. Radial basis function neural network is used. The performance of the proposed hybrid neuro fuzzy control is compared with PD adaptive control and fuzzy logic controller.

2. 1. 4. FLC and Feedback

In [14] the tip position control of a TLFM is studied using delayed feedback and fuzzy logic control technique. The model of the flexible manipulator is obtained using the AMM with an assumption of pinned-pinned beams.

2. 1. 5. FLC and Adaptive

Fuzzy learning and direct adaptive control (FLAC) is used in [15] for tip trajectory tracking control of a TLFM. Trajectory tracking control and tip deflection suppression are achieved in the presence of varying payloads. AMM is used to model the dynamics. Numerical simulations are done to generate the results.

2. 2. Artificial neural network (ANN)

It is difficult to design a controller without knowing system dynamics. In such cases, an ANN is more suitable. It is non modeled based intelligent control technique. Efficiency in building controllers for unknown dynamical systems and handling partially defined systems are the main advantages of this control technique. Feedforward and feedback network are the two types of ANN. An inverse dynamic model of a plant is used to train the network of the ANN. In direct learning algorithm, ANN copy the inverse dynamic model of the plant from the input and output of the plant. In indirect learning algorithm, ANN mimics the inverse dynamic structure of the plant. ANN is used in combination with other classical control and robust control for different control problems of a TLFM.

2. 2. 1. Conventional NN

In [16] the vibration control mathematical foundation is studied from a single link manipulator to a three-dimensional, two link flexible manipulator. The vibration control theory developed earlier feeds back a fraction of the link root strain to increase the system damping, thereby reducing the strain. This extension is supported by experimental results. Further improvements are proposed by tuning the right proportion of root strain to feed back, and the timing using artificial neural networks. The algorithm was implemented online in matlab interfaced with dSPACE for practical experiments. From the practical experiment done in consideration of a variable load, neural network tuned gains exhibited a better performance over those obtained using fixed feedback gains in terms of damping of both torsional and bending vibrations and tracking of joint angles.

In [17] a position/force control strategy is proposed for flexible-joint manipulator(FJRM) with uncertainties and disturbances. The radial basis function neural network(RBFNN) is used to estimate and compensate the unknown parts of the robot model. According to backstepping technology, a position/force control scheme is proposed to reduce the effect of unknown parts and system disturbances, and to improve the force tracking accuracy while ensuring the position control accuracy. The uniformly bounded of all signals of the closed-loop system is proved by the Lyapunov stability theorem. In the end, the proposed controller is applied to the two-rigid-link FJRM, and the simulation results show the effectiveness and feasibility of the proposed control scheme.

2. 2. 2. NN and PID control

Hybrid collected NN based MPC and non-collected PID controllers are designed in [18] for trajectory tracking control of a TLFM. In this, AMM is used to model the dynamics, and NN is used for identification of the dynamics. NNMPC is used for motion trajectory tracking and PID is designed for vibration control. Payloads are varied to study the effect on the performances of the controller. Results are simulated using MATLAB/Simulink environment.

In [19] data-driven dynamics analysis and controller design for a Flexible-Joint Robotic Manipulator (FJRM) are presented. The FJRM under study is a planar two-DOF manipulator with two flexible joints and two rigid links with a switched dynamic. The implementation hereby described is determined by a comparative analysis developed between direct and indirect data-driven controllers. Firstly, state-space feedback is proposed from an experimentally identified model as an indirect framework. Secondly, a Neural PID is designed and developed directly from data. The comparison results allowed to identify the most appropriate controller topology to implement.

2. 2. 3. ANN and LQR

Anti-windup saturation compensation is achieved in [20] during trajectory tracking control of a TLFM. Singular perturbation is used to divide the dynamics into slow and fast subsystems. NN is designed to control the saturation nonlinearity in a slow system and LQR is designed to attenuate the vibration in fast subsystem. Numerical simulations are performed.

2. 2. 4. ANN and H∞ control

In [21] tip position trajectory tracking control of a TLFM is studied using ANN and H∞ control. The dynamics of the manipulator are decomposed into a slow and a fast subsystem using AMM and singular perturbation theory. H∞ control is applied to the fast subsystem and decomposition-based control on the slow subsystem. To compensate the quasi-static deflection, a neural network compensation algorithm is used. Numerical simulations are performed.

2. 2. 5. ANN and adaptive control

In [22] the identification of a TLFM using an adaptive time delay neural network (ATDNN) is studied. Trajectory tracking is achieved using the proposed identification technique. The dynamic recurrent neural network is used. Selection criteria for selecting fixed structural parameter of the dynamics are also provided. Adaptation laws for updating the adjustable parameters of the network are also discussed. The proposed neuro dynamics are selected in series and parallel for training.

In [23] adaptive neural networks are used for control design using full-state feedback and output feedback separately to suppress the vibration of single-link flexible manipulator and highlighted better control performance than the PD control strategy. However, input nonlinearities were not considered in the control design.

In [24] the adaptive full state feedback neural network controller and the adaptive output feedback neural network controller is presented to suppress the vibration of a single-link flexible manipulator with input deadzone. Radial basis function neural networks are used to approximate the effect of input deadzone and unknown dynamics of the FLM.

Comparative study of model based and model free control of a TLFM is presented in [25]. It considered an inverse dynamics control as a model based control technique. Energy based control and neuro adaptive control are the two model free control techniques used. Inverse dynamics-based control is achieved using PID control. Energy based control is achieved using PD type control scheme and stability analysis is presented using Lyapunov stability theory. In this case, neuro adaptive recursive neural network is used. Position control, force control and vibration control are the three control problems considered in this paper.

In [26] with an uncertain two-link rigid–flexible manipulator with vibration amplitude constraint, position control is achieved via motion planning and adaptive tracking approach. In motion planning, the motion trajectories for the two links of the manipulator are planned based on virtual damping and online trajectories correction techniques. The planned trajectories can not only guarantee that the two links can reach their desired angles, but also have the ability to suppress vibration, which can be adjusted to meet the vibration amplitude constraint by limiting the parameters of the planned trajectories. Then, the adaptive tracking controller is designed using the radial basis function neural network and the sliding mode control technique. The developed controller makes the two links of the manipulator track the planned trajectories under the uncertainties including unmodeled dynamics, parameter perturbations, and persistent external disturbances acting on the joint motors. The simulation results verify the effectiveness of the proposed control strategy and also demonstrate the superior performance of the motion planning and the tracking controller.

In [27] the robust-adaptive neural network finite-time control and vibration suppression for a two-link flexible-base flexible-joint space manipulator with uncertain dynamics is studied. Based on the dynamic equations, a slow subsystem and a fast subsystem of flexible space manipulator are derived by the singular perturbation method. For the slow subsystem, a robust-adaptive neural network finite-time motion control scheme is proposed to achieve the trajectory tracking of the manipulator, taking into account both parameter uncertainties and external disturbances. This control scheme consists of a finite-time controller used to guarantee the finite-time convergence of system errors, an adaptive neural network controller utilized to approximate uncertain dynamics and a robust controller added to eliminate the approximation error of the neural network. For the fast subsystem, a linear quadratic optimal controller is introduced to suppress the vibration caused by flexible joints and the flexible base, respectively. The effectiveness and the superiority of the presented hybrid controller are indicated by the simulations with a planar two-link flexible-base flexible-joint space manipulator.

2. 2. 6. ANN and feedback linearization control

Tip position and trajectory tracking problems are considered in [29] using advanced control strategy. The control strategy is based on PDE and ODE model of the manipulator. PID and feedback linearization based control are considered as an enhanced control strategy. Gaussian ANN is used in this paper to train the parameters of the controller.

2. 2. 7. Neuro-SMC

Trajectory tracking control and vibration suppression of a TLFM are reported in [30] using neuro-SMC (NSMC). A singular perturbation technique is used to divide the dynamics of the manipulator. A NSMC is designed on slow subsystem for trajectory tracking and a normal SMC is designed for the flexible subsystem for suppressing the vibration of the link. Numerical simulations are performed.

In [31] sliding mode control for joint position control and vibration suppression of a single-link flexible manipulator is designed using an adaptive neural approximator to compensate for the modeling uncertainties and external disturbances.

2. 2. 8. STC using ANN and PI controller

Self-tuning control (STC) for a TLFM using neural network is presented in [32]. The proposed ANN controller in this paper learns the gains of PI controller. Joint angle tracking control and vibration suppression are considered as the control problem. System identification of the plant is achieved using the ARMAX (Auto-regressive moving average exogenous) model.

2. 2. 9. ANN and Computed torque control using visual sensor

End-effector trajectory tracking control of a TLFM is presented in [33] using visual sensor based NN. Computed torque (similar to feedback linearization) controller is designed for virtual rigid robot and vision feedback signal. The link deflections of the manipulators are also suppressed. Simulation and experimental results are performed for end-effector trajectory tracking control.

2. 2. 10. Weighted Multiple Neural Network Boundary Control

In [34] the angle tracking and vibration suppression for a flexible manipulator with uncertain parameters is studied. Based on the partial differential equation (PDE) model, a unified framework of weighted multiple neural network boundary control (WMNNBC) is proposed to deal with the jumping parameters, in which neural networks are designed as the local boundary controllers to suppress vibrations. A novel proportion-derivative-like machine learning algorithm is developed to guarantee the learning convergence. Besides, the weighting algorithm is used to fuse multiple local neural network controllers to generate the appropriate global control signals with the variations of plant parameters. The stability of the overall closed-loop system is proved by the virtual equivalent system (VES) theory. The simulations are implemented to illustrate the feasibility and control performance of the proposed WMNNBC strategy.

2. 2. 11. self-tuning strain feedback gain controller Using ANN

In [35] a self-tuning strain feedback gain controller for high-speed vibration control of a 3D two-link flexible manipulator using the artificial neural network is presented and highlighted that the tuned gains achieved better performance than that achieved by using fixed gain in terms of link strain and joint trajectories

2. 2. 12. learning control of FLM using neural networks

In [36] the singular perturbation theory based composite learning control of FLM using neural networks and disturbance observer is studied. Sliding mode control was used for the fast dynamics and intelligent control based on neural network, and disturbance observer was used for the slow dynamics.

In [37] a reinforcement learning control is investigated to suppress the vibration of a single-link flexible manipulator using two radial basis function neural networks: actor neural network to design proper control input and critic neural network to approximate the cost function of the system.

2. 2. 13. diagonal recurrent neural network control technique

In [38] a diagonal recurrent neural network control technique is used for the vibration control of the single-link flexible manipulator using non-contact vibration measurement based on structure light sensor. They also proposed a trajectory optimization technique to obtain optimal vibration suppression trajectory using the particle swarm optimization algorithm.

2. 2. 14. Neural Network Control Using Assumed Mode Method

In [39] full-state and output feedback neural network controllers are studied for a two-link flexible manipulator based on a radial basis function neural network to achieve trajectory tracking and vibration suppression. They claimed that the proposed adaptive neural network controller had better performance than the PD controller.

In [39], the n-dimensional discretized model of the two-link flexible manipulator is developed by the assumed mode method (AMM). Subsequently, based on the discretized dynamic model, both full-state feedback control and output feedback control are investigated to achieve the trajectory tracking and vibration suppression. In order to guarantee the stability strictly, uniform ultimate boundedness (UUB) of the closed-loop system is realized by the Lyapunov's stability. Furthermore, through appropriately choosing control parameters, the states of the system will converge to zero within a small neighborhood. Eventually, extensive simulations and experiments on the Quanser platform for a two-link robotic manipulator are carried out to demonstrate the feasibility of the proposed neural network controller.

2. 3. Genetic algorithm (GA)

It is a non-modeled based intelligent control technique. It uses a search procedure based on the mechanism of natural selection. It belongs to the class of heuristic method and considered as a stochastic search algorithm. GA search for the best possible solution of optimization problems using mimic of genetic dynamic of natural evolution. GA methods can be used either off-line or online. GA is used in combination with other classical control and robust control for different control problems of a TLFM.

2. 3. 1. GA and SMC

Terminal SMC control is presented in [40] to represent the non-minimum phase characteristic using the output redefinition matrix for a TLFM. Manipulator dynamics is decomposed into an input-output subsystem and zero dynamics subsystem using the input-output linearization technique. To control the input-output subsystem, a SMC is designed. Relation between eigenvalue of the zero dynamics and parameters of the refined output is also obtained. To show the stability of the zero dynamics and entire manipulator dynamics, parameters of the controller are optimized using GA. Higher order nonsingular terminal SMC (HONTSMC) is designed in [41] to control the position of a TLFM in the presence of uncertainty. Third order NTSMC is designed for stabilization of the input-output linearized dynamics in the absence of chattering. GA is used to optimize the controller gains. Results are shown using simulation. Optimized continuous NSTM is used in [42] for controlling the position of a TLFM. The controller is designed for an input-output subsystem to suppress the chattering and stabilize the dynamics. GA is used for optimizing the parameters of the controller. Results are validated using simulation.

Optimized continuous NSTM is used in [43] for controlling the position of a TLFM in the presence of uncertainty and disturbances. Continuous NSTM is designed using SMC, and gains of the controller are optimized using GA technique. The input-output subsystem is obtained to design the controller. Results are shown using simulation.

Hybrid fuzzy non singular terminal SMC (NSTM) along with GA is proposed for tip position control of a uncertain TLFM [44]. The dynamics is decomposed into input-output subsystem and zero dynamics subsystem using output redefinition method. Fuzzy NSTM is designed for input output subsystem and fuzzy is used to reduce chattering in SMC. The zero dynamics subsystem is controlled using GA.

Lyapunov stability theory is used for stability analysis of the system and AMM is used for modeling of the manipulator dynamics.

2. 3. 2. GA and PD

Tip position control of a TLFM is presented in [45] using evolutionary computing based PD control technique. The evolutionary computing technique consists of a genetic algorithm and bacteria foraging optimization is used for optimizing the parameter of the PD controller. The results are demonstrated using numerical simulations.

Evolutionary computation approaches to tip position controller design for a two-link flexible manipulator Controlling multi-link flexible robots is very difficult compared rigid ones due to inter-link coupling, nonlinear dynamics, distributed link flexure and under-actuation. Hence, while designing controllers for such systems the controllers should be equipped with optimal gain parameters. Evolutionary Computing (EC) approaches such as Genetic Algorithm (GA), Bacteria Foraging Optimization (BFO) are popular in achieving global parameter optimizations. In this paper we exploit these EC techniques in achieving optimal PD controller for controlling the tip position of a two-link flexible robot. Performance analysis of the EC tuned PD controllers applied to a two-link flexible robot system has been discussed with number of simulation results.

2. 3. 3. GA and fuzzy

In [46] a fast, stable control technique is presented based on system energy for a planar single-link flexible manipulator for joint position control and vibration suppression. Moreover, they proposed an online optimization method based on fuzzy-genetic algorithm.

In [47], tip position and vibration suppression control for a TLFM using GA are presented based on a hybrid FLC strategy. Uncouple FLC is used along with individual controller at the shoulder and elbow link of the manipulator. GA is used to extract the rule base of the FLC. A scaling factor of the FLC are tuned with GA to improve the performance. FEM method is used to model the manipulator dynamics.

2. 3. 4. GA optimized feedback and adaptive control

Tip position control of a TLFM is in [48] using GA optimized feedback and adaptive control. First dynamic state feedback control is used for vibration suppression and regulation of the rigid modes. To compensate the payload changes and external disturbances, feedback control is used along with adaptive control. The gain of the controller is optimized using GA. An AMM is used for modeling the dynamics of the manipulator.

Optimal trajectory control of a PDE modeled TLFM is presented in [49] using feedback control and GA. Optimal trajectory is generated using differential evaluation GA for minimizing the total energy consumption. Feedback boundary control is used to regulate the link in the optimized trajectory and to suppress the vibration in the links of the manipulator.

3. Conclusion

Robotic manipulators are highly demanded to work in dangerous, routine, and difficult jobs instead of human in order to achieve accurate, faster, and economical operations. Manipulators are divided as rigid manipulator and flexible manipulator (FM). In this paper, FMs are considered because of their several advantages over rigid manipulators. Some important advantages of the FMs can be listed as low energy consumption, smaller size, economical, light weight, more workspace, portability.

The studies on TLFMs are classified into three main categories as modeling methods, dynamical analyses and control techniques. Different kinds of control problems exist for a two-link flexible manipulator, which include position control, tip position control, trajectory tracking, tip position trajectory tracking, vibration control, force control, motion control and hybrid of the above-mentioned control problems.

In this paper, Intelligent control schemes applied to TLFMs are presented as fuzzy logic control-based schemes, Genetic algorithm-based schemes and Artificial neural network (ANN)-based schemes.

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