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Robust control schemes in flexible manipulators: A review

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Abstract - In this paper, flexible manipulators are considered because of their several advantages over rigid manipulators, and a survey in the field of two-link flexible manipulators (TLFMs) is presented. Two-link flexible manipulators are more used in comparison with other types of flexible manipulators. 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. In this paper, a comprehensive review of robust control schemes applied to TLFMs is presented.

Keywords: Flexible manipulators, Robust control, sliding mode control, adaptive control, backstepping control, observer

1. Introduction

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 [1]. Manipulators are divided as 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 [2]. However, the limitations of flexible manipulator are control complexity [3], uncertainties [4] and MIMO and nonlinear systems [5]. 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. 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, robust control schemes applied to TLFMs are presented as Sliding mode control (SMC), Adaptive control, H2 and H∞ control, Observer-based control, LQG (Linear quadratic Gaussian), Backstepping control and robust proportional derivative. In Sliding mode control schemes, Conventional SMC, SMC and PID control, SMC and state feedback control, SMC and variable structure control, Terminal SMC, Hierarchical sliding mode control, SMC and LQR and Asymptotic SMC and PI-SMC are studied. In Adaptive control, Adaptive and LQG control, Adaptive and feedback control, Adaptive and SMC control schemes, Adaptive boundary control, Adaptive and PD and PID control, Adaptive dynamic programming, adaptive inverse controller based on model-reference, Adaptive intelligent-based control, Adaptive and reinforcement or iterative learning, Adaptive and model predictive control, Adaptive and gain scheduling and Adaptive and LQR control scheme are reviewed. In H2 and H∞ control, Hybrid Sliding Mode/H-Infinity Control, Adaptive and H∞ control, LMI-based H2 and H∞, Feedback controller based on H∞ loop shaping and H2 (Gain scheduled strictly positive real control) are presented. In Observer-based control, Disturbance observer based control, State observer, State observer and backstepping control, reduced-order extended state observer, SMC and Observer-based control, PDE robust observer, neural networks (NNs) and disturbance observer (DOB) and optimized time-variant observer are reviewed. In LQG (Linear quadratic gaussian), LGQ and feedforward control and LQG and LTR (Loop transfer recovery) are studied. Thereafter Backstepping control and Robust proportional derivative are presented.

2. Robust control

Variable structure control, sliding mode control (SMC), adaptive control, H∞ control, backstepping control and disturbance observer are the main types of robust control techniques. In real practice, dynamics of the plant is affected by the uncertainties (model uncertainty, parametric uncertainty, etc.) and disturbances (associated with input, output and plant, etc.). Thus, it requires robust control techniques to deal with these extra challenges associated with the plant.

2. 1. Sliding mode control (SMC)

It is a non-model based robust control technique. It is robust to model uncertainty, inaccuracy, consistence in performance, order reduction, insensitive to parameter variation. The design of SMC consists of two steps: first is to design a sliding surface/ sliding variable and then is to design a sliding mode control law. The various structures of the sliding variable are proposed in the literature.

2. 1. 1. Conventional SMC

Distributed control strategy is designed in [6] for trajectory tracking and vibration control of a TLFM using numerical methods. The distributed control strategy is designed in [6] using decomposing the dynamics into two subsystems. Each subsystem consists of one-link and one joint. Conventional SMC is used to control each subsystem. Results are simulated and compared with results of PID controller.

Trajectory tracking control of a TLFM is presented in [7] using conventional SMC. Numerical simulation is performed to obtain the results.

Design of a controller for joint trajectory tracking for two-link flexible manipulator (TLFM) in presence of vibration, model uncertainty and external disturbance is a considered in [8]. To deal with these problems, in this work Sliding Mode Controller (SMC) has been designed. Equivalent viscous damping coefficient (EVDC) has been considered as model uncertainty.

2. 1. 2. SMC and PID control

A terminal SMC is designed in [9] for tip position control using the output redefinition method for a TLFM. In this, the manipulator dynamics are divided into input-output dynamics and zero dynamics. SMC is also used in combination with a PID control for different control problems of a TLFM.

PID sliding surface type SMC is designed in [10] to track the chaotic signal in the presence of bounded disturbances and to regulate the tip deflection to zero. The desired chaotic trajectory is generated using Genesio-Tesi chaotic system. Lumped parameter model is used for modeling of the manipulator dynamics.

2. 1. 3. SMC and state feedback control

Tip position control of a TLFM is given in [11] using a hybrid actuator scheme. The AMM is used for modeling the dynamics of the manipulator. The scheme combines the actuators using two servo motors at the hub and two piezoceramics attached on the surface of the link. Two sliding hyperplanes with time varying parameters are designed for two servo motors. Pole placement technique is used to design the variable of the hyperplane. Feedback control voltage is applied on piezo ceramic actuators to suppress the undesirable torque caused by the rigid body dynamics.

2. 1. 4. SMC and variable structure control

A variable structure control is used in [12] for joint angle trajectory control of a TLFM. Robust tracking control of a TLFM is achieved in the presence of payload uncertainty. A sliding mode control algorithm is presented for Cartesian trajectory control of a three-axis flexible manipulator by using the theory of variable structure systems. The manipulator has two rigid links and the third link is elastic. A parameterization of the Cartesian coordinates of a point close to the end-effector position is suggested. Using these coordinates as output variables, a discontinuous output control law is derived based on the variable structure theory for tracking reference Cartesian trajectories. To regulate the end point to a fixed position, a linear stabilizer is designed to damp the elastic vibration.

2. 1. 5. Terminal SMC

In [13], a robust finite-time disturbance attenuation tracking control strategy of flexible-joint robotic systems affected by unpredictable matched and unmatched time-varying disturbances is presented in this work. By considering all the disturbances as an unknown total time-varying disturbance, a dynamic model with the flatness description of the FJR is firstly deduced. Then, a new dynamic terminal sliding mode surface is designed with the assistance of the estimates from a constructed sliding mode observer (SMO). Meanwhile, the continuous terminal sliding mode control (CTSMC) technique is employed to develop a finite-time disturbance attenuation control methodology. Besides, the finite-time stability of the closed-loop system acting on the proposed control framework is guaranteed.

In [14], the transient analysis for a two-link flexible manipulator under the control of non-singular terminal sliding mode (NTSM) is studied, and proposes a convergence time estimation method with difficulties of non-minimum phase and the uncontrolled reaching motion.

In [15], the decoupling control of two-link flexible manipulators with uncertain parameters and joint motor dynamics is investigated by combining terminal sliding mode (TSM) and output redefinition in this paper. The linear combination of joint angles and flexible modes is chosen as the redefined output to overcome the inherent non-minimum phase characteristics.

In [16], the dynamic model of the two-link flexible manipulator with payload is analyzed using Euler-Lagrange equation. And then, a fast nonsingular terminal sliding mode controller is proposed for trajectory tracking problem of the manipulator. The stability of the control system is proved by the Lyapunov theory.

2. 1. 6. Hierarchical sliding mode control

In [17], a hierarchical sliding mode control (HSMC) for a rotary flexible joint manipulator (RFJM) is presented. Firstly, the rotary flexible joint manipulator is modeled by two subsystems. Secondly, the sliding surfaces for both subsystems are constructed. Finally, the control action is designed based on the Lyapunov function.

In [18], the control motion of a single link flexible joint robot by using a hierarchical non-singular terminal sliding mode controller (HNTSMC) is studied. In comparison to the conventional sliding mode controller (CSMC), the proposed algorithm (NTSMC) can conserve characteristics of the convention CSMC, such as easy implementation and the guaranteed stability.

2. 1. 7. SMC and LQR

In [19], two laws are presented as nonlinear sliding mode control (SMC) and linear quadratic regulator (LQR) for addressing the control problem of flexible joint manipulators.

Trajectory tracking control of a TLFM is proposed in [20] using an optimal (LQR) and SMC control. The dynamics of the manipulator are divided into slow and fast subsystem. LQR and SMC are used to design different control strategy for slow and fast subsystem, respectively.

2. 1. 8. Asymptotic SMC and PI-SMC

Tip position control of a TLFM using an asymptotic SMC and PISMC is reported in [21]. It is shown that the chattering is attenuated using the used SMC control technique even in the first order SMC. The robustness of the proposed control techniques is verified under parametric uncertainty and bounded disturbances. The lumped parameter model is used for modeling of the manipulator dynamics.

2. 2. Adaptive control

Direct and indirect adaptive controls are the main types of adaptive control. Insensitive to parametric uncertainties, varying payload or unknown disturbances are the main advantages of an adaptive controller. This parameter adaptation mechanism is estimated directly from the motion tracking error in the case of direct adaptive control. On the contrary, in the indirect adaptive control, parameters of the system are updated using online estimation. The structure of the direct adaptive control for two-link flexible manipulator is given as [22].

2. 2. 1. Adaptive and LQG control

The identification and control of a very flexible TLFM is presented in [23]. A parametric frequency domain identification technique is applied to obtain the linear SISO model. A gain scheduled compensator i. e. LQG is developed on the linearized model to control the joint angle and results are validated using numerical simulations and experiments.

2. 2. 2. Adaptive and feedback control

Adaptive augmented state feedback control is designed in [24] for tip trajectory tracking control of a TLFM. The controller is designed using LQR and adaptive compensator. An adaptive compensator is designed using strong tracking filter for estimation of the states. The results are verified using simulation and experiment.

Model reference adaptive control is designed for the position and trajectory tracking control of a TLFM [25]. Feedforward compensator is designed for validating the linear model of a nonlinear dynamics. AMM is used for modeling the dynamics of the manipulator. The results are presented using numerical simulations.

In [26], a filtered feedback linearization controller is presented for the simultaneous positioning and vibration suppression of a single-link flexible manipulator that requires limited model information, specifically, knowledge of the vector relative degree, and knowledge of the dynamic-inversion matrix. Additionally, the filtered feedback linearization controlleras combined with a high-gain adaptive law for robust control and addressed the problem of model uncertainty.

2. 2. 3. Adaptive and SMC control schemes

Two types of SMC with and without adaptive control techniques are presented by [21] for position control of a TLFM. Adaptive control is used when the parameters of the manipulator are unknown and external disturbances added to the dynamics. Quasi and conventional SMC are designed. Lumped parameter modeling method is used for modeling the manipulator dynamics. Numerical simulations are performed. Tip trajectory tracking control of a TLFM is presented in [27]. Separately an adaptive and a SMC are designed for the control problem. The model of the manipulator is derived using the FEM method. The results are validated using numerical simulation.

Tip position control of a TLFM is proposed [28] using hybrid sliding mode consisting of frequency shaped optimal sliding mode control (FSOSMC) and terminal SMC (TSMC). Adaptive variable structure control is designed to estimate the upper bounds on the norm of uncertainties. The dead zone scheme is also introduced to improve the system robustness.

In [29] a composite control strategy is presented for a flexible space manipulator as a combination of an adaptive sliding mode controller for the slow subsystem and an adaptive controller for the fast subsystem.

2. 2. 4. Adaptive boundary control

Position control of a PDE modeled TLFM is presented in [30] using the adaptive boundary control technique. PDE model is developed to reduce the spillover problem caused by neglecting flexible modes. Vibration is also suppressed using the proposed technique. The results are presented using numerical simulations.

2. 2. 5. Adaptive and PD and PID control

An adaptive PID controller is presented in [31] for the joint position and tracking control of a single-link flexible manipulator, which may automatically online tune the control gains to accommodate the actuator fault

Two types of adaptive energy-based controllers are proposed in [32] for position control of a TLFM. The first controller consists of a joint PD controller and an adaptive proportional controller to suppress the vibration. Second controller consists of a Lyapunov based PD controller for position control.

2. 2. 6. Adaptive dynamic programming

The problems of tip position regulation and vibration suppression of FLM is presented in [33] using model-free composite control based on adaptive dynamic programming.

2. 2. 7. adaptive inverse controller based on model-reference

In [34] The elastic vibrations of two-link manipulators are decoupled from the flexible manipulator for vertical planar two-links flexible manipulators. And the system was decomposed into two subsystems, slow-changing subsystem and fast-changing subsystem. An adaptive inverse controller based on model-reference is established for slow-changing subsystem. The fast-changing subsystem was deal with as disturb signal from system.

2. 2. 8. Adaptive intelligent-based control

In [35] For the trajectory tracking and vibration suppression of a two-link flexible robot, a neural networks based fixed-time control method is proposed, which takes into account the system uncertainty, output constraint and input saturation. Novel adaptive law and virtual control are designed for the solution of the system uncertainty in the fixed-time convergence settings. The barrier Lyapunov function (BLF) is used to solve the output constraint problem of the system. Furthermore, control chattering is discussed in detail.

In [36] An adaptive fuzzy control strategy is proposed for a single-link flexible-joint robotic manipulator (SFRM) with prescribed performance, in which the unknown nonlinearity is identified by adopting the fuzzy-logic system. By designing a performance function, the transient performance of the control system is guaranteed. To stabilize the SFRM, a dynamic signal is applied to handle the unmodeled dynamics. To cut down the communication load of the channel, the event-triggered control law is developed based on the switching threshold strategy. The Lyapunov stability theory and backstepping technique are applied coordinately to design the control strategy.

2. 2. 9. Adaptive and reinforcement or iterative learning

Tip trajectory tracking and tip deflection suppression of a TLFM with variable payloads is proposed in [37] using adaptive and reinforcement learning (RL) control techniques. PD based adaptive controller and an actorcritic-based RL are used. Recursive Least Squares (RLS) based temporal difference (TD) learning is used for estimating the critic weights, and gradient based estimator for estimating actor weight. The proposed controller is compared with direct adaptive control and fuzzy adaptive controller. AMM is used for modeling the dynamics of the manipulator.

An adaptive boundary iterative learning control scheme with a PD feedback structure is presented in [38] or the joint trajectory tracking and vibration suppression of a two-link rigid-flexible manipulator with parametric uncertainties and external disturbances.

An adaptive iterative learning control scheme for joint position tracking and vibration suppression of a single-link flexible manipulator is presented in [39] in the presence of external disturbance and output constraints.

In [40], An adaptive distributed iterative learning control by combining a PD feedback structure and an iterative term for simultaneous trajectory tracking and vibration suppression of a single-link flexible manipulator subjected to system parameters uncertainties and spatio-temporal distributed disturbances.

In [41] an adaptive iterative learning vibration control (AILVC) scheme is considered for a two-link rigid-flexible manipulator with endpoint input saturation. A PD-type AILVC law is designed for the coupled ordinary differential equation - partial differential equation dynamic model in the presence of time-varying disturbances and the distributed disturbance.

2. 2. 10. Adaptive and model predictive control

Tip position control of a TLFM handling different payloads using nonlinear adaptive model predictive control (NAMPC) is presented in [42]. ARMAX technique is used for system identification. Performance of NAMPC is compared with the self tuning controller (STC) and direct adaptive controller (DAC). In [42] the tip trajectory tracking and vibration suppression as the performance measure are considered. AMM is used for modeling the dynamics of the manipulator.

2. 2. 11. Adaptive and gain scheduling

Decentralize gain scheduling adaptive control is used in [43] for tip position control of a TLFM. The control scheme is also applied for handling unknown payload and vibration suppression. Tip position control of a TLFM is discussed in this paper using self-tuning adaptive control with unknown payload. System identification is also presented.

2. 2. 12. Adaptive and LQR control scheme

Position control of TLFM with variable payloads is reported in [44]. It is based on adaptive and RL control scheme. The LQR based decentralized controller is designed for the decoupled system. In this, RL is used to tune the gain of LQR. The results are obtained using numerical simulations.

Adaptive augmented state feedback control (AASFC) technique is designed in [45] for tip position and trajectory tracking control of a TLFM. The control in [45] consists of steady state LQR technique in conjugation with an adaptive compensator, and STR (Strong Tracking Filter) for estimating the state.

2. 3. H2 and H∞ control

It is non modeled based robust control technique. The controller is robust to model uncertainty, inaccuracy and is consistence in performance, order reduction and is insensitive to parameter variation.

2. 3. 1. Hybrid Sliding Mode/H-Infinity Control

In [46], a hybrid control approach combining sliding mode and H-infinity is proposed for an uncertain single-link flexible manipulator. The sliding mode controller stabilizes the nonlinear manipulator system, while the H-infinity controller enhances the noise rejection capability of the system by reducing the total system nonlinearity.

2. 3. 2. Adaptive and H∞ control

The model reference adaptive H∞ control is designed in [47] to handle unknown input nonlinearities such as dead-zone and backlash. The control scheme is designed for a mixed parameter system composed of distributed parameter systems of hyperbolic type (flexible arm) and lumped parameter system (motor control system). Adaptive control is used to estimate and compensate the input nonlinearities. H∞ control is designed to regulate the effect of the spillover term.

2. 3. 3. LMI based H2 and H∞

LMI based gain scheduled controllers are designed for trajectory tracking control of a TLFM in [48]

the performance of the controller is shown on a AMM modeled TLFM. The results are demonstrated using numerical simulations.

2. 3. 4. Feedback controller based on H∞ loop shaping

Trajectory tracking control and vibration suppression of a TLFM is reported in [49] using a feedback controller based on H∞ loop-shaping design and a feedforward compensator. Results are obtained using numerical simulation.

2. 3. 5. H2 (Gain scheduled strictly positive real control)

Tip position control of a TLFM is presented in [50] using gain scheduled strictly positive real controller. The AMM method is used for the manipulator dynamic modeling. The linear SPR controller is optimized using gain scheduled controller. The results are demonstrated using numerical simulations.

2. 4. Observer based control

In Observer based control, Disturbance observer based control, State observer, State observer and backstepping control, reduced-order extended state observer, SMC and Observer based control, PDE robust observer, neural networks (NNs) and disturbance observer (DOB) and optimized time-variant observer are reviewed.

2. 4. 1. Disturbance observer-based control

It is a model based robust control technique. Independent joint control without considering the coupling effect of other link is the main advantages of this control technique. The disturbance observer uses the difference between the actual input torque and the inverse of the output of the nominal model as the equivalent disturbance applied to the nominal modal. To cancel the actual disturbance, equivalent disturbance is feedback through a lowpass filter.

Disturbance observer is used in [51] to compensate the disturbance for position control of a TLFM. The lumped parameter method is used for modeling of TLFM.

In [52], the boundary disturbance observer-based control for a vibrating single-link flexible manipulator system possessing external disturbances. Two new boundary anti-disturbance control strategies are presented to eliminate vibration, track disturbance, and determine angle position for the flexible manipulator system.

2. 4. 2. State observer

In [53], a stepping control based on extended state observer (ESO) based is developed to track the trajectory of a two-link flexible manipulator. The link is flexible and coupled making the system sensitive to uncertainties, while the controller design requires exact information of the system modeling. To avoid these issues, an ESO is introduced to estimates the uncertainties as well as the system state vector. The back stepping controller is then studied uses the states estimated by ESO. Stability of this nonlinear coupled two-link system is then achieved using Lyapunov-based methods.

2. 4. 3. State observer and backstepping control

Trajectory tracking control of a linear flexible TLFM is presented in [54]. Linear flexible system is obtained using nonlinear decoupling feedback control. An extended state observer is used to estimate the system nonlinear part and backstepping control is used for the trajectory tracking control of the manipulator. Results are obtained using numerical simulation.

2. 4. 4. reduced-order extended state observer

In [55], we take a two-link FJM with complex uncertainties as the object, and present a command filtered backstepping control approach based on reduced-order extended state observer (RESO) for the trajectory tracking control of the two-link FJM with high precision. To enhance the robustness of the control system, an RESO which takes parameter perturbations, friction term and external disturbances as the lumped disturbances is constructed to estimate and compensate for the disturbances. The second-order command filter technique is introduced to eliminate the “explosion of complexity” problem of the conventional backstepping method, and an error compensation dynamic system is developed to reduce the potential filtering errors. All signals of the closed-loop system are proved to be uniformly ultimately bounded by Lyapunov theorem.

2. 4. 5. SMC and Observer based control

Hybrid control scheme is used in [56] to control the position of a TLFM. Hybrid controller is designed using continuous nonsingular terminal SMC and observer based LQR control techniques. Singular perturbation is used to divide the FM dynamics into two parts: slow and fast subsystems. For slow subsystem, a continuous nonsingular terminal SMC is designed and for fast subsystem an observer based LQR controller is designed. The observer is designed to estimate the flexible modes and LQR is designed to stabilize the modes

In [57], the robust position tracking control of a two-degree-of-freedom serial flexible link (2DOFSFL) robot. With a disturbance observer (DO), the robust backstepping sliding mode controller which combines both the merits of the backstepping control and sliding mode control, is proposed to deal with the position tracking control problem of a 2DOFSFL robot i... Show More

In [58], an observer-based robust fault diagnosis scheme is proposed to diagnose actuators in flexible joint robot manipulators. Specifically, the original system is decoupled into two reduced-order subsystems using linear non-singular transformation method. Then, a robust fault diagnosis scheme based on sliding mode observer is designed to detect and further estimate actuator faults in nonlinear systems.

2. 4. 6. PDE robust observer

In [59] a boundary controller for the FLM based on the PDE robust observer is presented to achieve the stability control, regulate the joint position, and suppress elastic vibration.

2. 4. 7. Neural networks (NNs) and disturbance observer (DOB)

In [60], the singular perturbation (SP) theory-based composite learning control of a flexible-link manipulator using neural networks (NNs) and disturbance observer (DOB) is studied. For the dynamics, the system states are separated into fast and slow variables in terms of time scale. For the multi-input-multi-output slow dynamics, the intelligent control is designed where NNs are u... Show More

2. 4. 8. Optimized time-variant observer

In [61], an observer is proposed for deflection error estimation. In this regard, by implementing an optimal observer on two types of manipulators, its effect and accuracy were compared for two cases. The difference between the two manipulators is in the number of actuators, the number of links, and the time-varying system dynamics. First, the observer with the Kalman filter structure, which is an optimized estimator, is applied to the dynamic model of a single-link flexible manipulator with a revolute joint. In the second case, the observer is applied to a two-link flexible manipulator with two revolute joints.

2. 5. LQG (Linear quadratic gaussian)

The LQG control is useful for controlling robot manipulator when the dynamics is considered with noisy input. The use of LQG with some other control technique is highlighted in the following points: Hybrid position and force control technique for a TLFM are presented in [62] using reduced order and full order LQG control technique. The results are presented using numerical simulation and experiment.

2. 5. 1. LGQ and feedforward control:

Trajectory tracking control of a TLFM is presented in [63] using modeled based LQG and feedforward control. Feedback gain is determined using LQG regulation theory. FEM is used for modeling the dynamics of the manipulator.

2. 5. 2. LQG and LTR (Loop transfer recovery)

In [64], the trajectory tracking control of a TLFM using combination of different robust control techniques is presented. LQG, LQG/LQR, LTR and 7th order LQG/LTR, 7th order reduced LTR, 4th order SANDY optimization techniques are the different control methods used. The lumped parameter method is used for the modeling of manipulator dynamics.

2. 6. Backstepping control

This is a non-model based robust control technique. Handling bounded disturbances and uncertainties are the main advantages of backstepping control technique.

Tip trajectory tracking control and vibration suppression of a TLFM is presented in [65] using backstepping control technique. The performance of the proposed controller is compared with the PD controller. The motion equation of the manipulator is developed using the projection equation and Ritz expansion technique.

In [66], an adaptive fault-tolerant controller using the backstepping technique for a flexible manipulator with bounded disturbance, actuator partial failure, and output constraints.

2. 7. Robust proportional derivative

In [67] a robust PD controller based on linear matrix inequality for joint position control of the two-link flexible manipulator under various payload conditions. They claimed that the proposed control provided better robustness and system performance compared to Ziegler-Nichols tuned PD controller.

3. Conclusion

In this paper, FMs are considered because of their several advantages over rigid manipulators. 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, robust control schemes applied to TLFMs are presented as Sliding mode control (SMC), Adaptive control, H2 and H∞ control, Observer based control, LQG (Linear quadratic gaussian), Backstepping control, Robust proportional derivative.

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