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Robust Control Methodologies and Applications for Robotic Systems

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Abstract. In performing tasks in complex unstructured settings, robots often face model uncertainties, external perturbations, actuator nonlinearities and failures. Regarded as the primary tool in ensuring that the system is stable and the precision of tracking is achieved, robust control has developed in a rapid way in recent years. In this paper, the current developments in robust control of robotics are reviewed in a systematic manner, in which the most advanced methods are divided into five groups based on theoretical backgrounds: $H\infty$ control, sliding mode control, model predictive control, adaptive control, and observer-based control. The operating principles, improvement plans and common uses of all these approaches are explained in detail. The paper below focused on summarizing robust control designs and engineering applications of collaborative robots, mobile robots, legged robots, space robots and other robotic systems. The main issues in the modern research arise such as disturbance modeling, computational performance, multi-constraints, and experimental verification. Eventually, future perspectives orient at the combination of robust control with intelligent perception, digital twin, and reinforcement learning. It is hoped that the present paper will be helpful to the researchers who want to study and select high-precision, high-reliability and high-stability control algorithms in the current robotic systems.

Keywords: Robust control, robotic systems, uncertainty compensation, disturbance rejection, fault-tolerant control

1. Introduction

The development of robot technology is rushing towards the artificial integration, various robots coordination and environmental complexity adaptation, and performing high-precision and safety-needed tasks in industry assembly, medical rehabilitation, space exploration, emergency rescue and other areas of extreme engineering. In actual robotic systems, there remain uncertainties like joint flexibility, frictional nonlinearity, loading changes, unknown external disturbances, degradation, and faults of actuators. Nevertheless, ordinary PID and inverse dynamics control techniques cannot guarantee steady convergence and desirable dynamic behavior when it comes to these unfavorable conditions.

Aiming at reducing uncertainty and providing limited stability, robust control relies less upon precise mathematical models, which is capable of sustaining constraint fulfillment and the required performance in the face of disturbances, so it takes a central role in robotic control studies. Over the past several years, researchers all over the world have conducted many studies on the theoretical basis, the structures of the algorithms, and the engineering realization of robust control of robots which have formed a multi-paradigmatic development pattern. The $H\infty$ control of disturbances is achieved by minimizing the sensitivity function and has found wide use in manipulator path tracking and flexible dynamics systems. Sliding-mode control boasts fast response and high disturbance rejection ability, by which the problem of chattering can be solved. It combines constrained optimization with robust invariant sets to be applicable to obstacle avoidance and formation control of mobile robots. Adaptive robust control achieves online estimation of uncertain parameters and minimizes dependence on past knowledge of the system. The integration of disturbance observers, extended state observers, and the algorithms allow feeding forward compensation and are highly effective in improving control accuracy.

Although the current research is productive, the available literature has significant shortcomings: the integrated modeling of composite perturbations remains imperfect; higher order systems are prone to significant online computational loads; safety constraints, interaction constraints, and strong performance are not easy to balance; most validation outcomes simulate, and there are few cross platform standardized experimental tests. The present paper discusses in depth the concept of robust control in the field of robotics in four aspects namely methods classification, applications, existing issues, and future perspectives, which gives an explicit structure on the way forward of the research.

2. Fundamental theory and problem modeling of robust control for robots

Robust control is based on proper representation of dynamic characteristics and environmental conditions in which robots operate. In order to bring together rigid manipulators, mobile robots on wheels, legged robots, and other platforms into the perturbed Euler-Lagrange dynamic model, robust control examine the underlying mechanisms of various negative influences such as model uncertainties, internal and external disturbances, and actuator failures. Using these assumptions, a control system with stability, convergence and constraint guarantee is built. It aims at realizing global stability and uniformly ultimately bounded tracking error under different bounded uncertainties and unknown disturbances, input-state constraints, fault tolerance and rapid dynamics response, thereby providing a theoretical and methodological basis of reliable robot operation in unstructured environments that are both complex and uncertain.

The dynamics of rigid manipulators, wheeled mobile robots, and legged robots may be written in a common form of perturbed Euler-Lagrange equations, which are accurate representation of the real dynamic behavior of robotic systems. A unified modelling framework offers a uniform theoretical foundation on which the controller design of various robot configurations is established on allowing the transfer of robust control algorithms between single-type robots and multi-type robots without altering the fundamental theoretical framework.

Different kinds of uncertainties and disturbances widely exist in robotic systems and affect performance devastatingly, with representatives such as perturbation in the inertial matrix, end-effector payload changes and parameter identification errors. The internal disturbances are due to the robot itself which comprises time-varying joint friction, actuator saturation and hysteretic nonlinearity. External disturbances arise from the interaction of the robot with the surrounding environment, i.e., contact forces, impact shocks, and environmental noise. Moreover, actuator failures like partial failure, locking, and bias drift also inject more complexity into system control.

The underlying issues in the robotic robust control deal with the aim of providing a stable and reliable performance in complex disturbances. Assuming that both perturbations and disturbances are bounded, the proposed control law should meet several key performance requirements, namely, global stability, uniformly ultimately bounded tracking errors, input and state constraints, high fault tolerance and rapid convergence rate, all of which are essential in high-risk and precision-needed systems.

3. Mainstream robust control methods and research progress

3.1. H∞ robust control

H∞ control seeks to reduce the gain of the transfer function between external interference and tracking errors and controllers are computed using Riccati equations or linear matrix inequalities (LMIs) with a strong theoretical background and rigid stability assurances. Zeyu Chen and Yipeng Lan used both the H2/H8 robust control and LMI methods to develop an H2/H8 hybrid control, which owned fast convergence properties and sensitivity to responses [1]. Common applications include manipulator trajectory tracking, flexural joint vibration suppression, and space robot system attitude stabilization. The future developments will move towards time varying H∞, decentralized H∞ and output feedback H∞ control structures. Chang Sheng, Hongfei Liu, Naiwei Zou et al. came up with a dynamic vehicle model, formulated the appropriate transfer functions in order to obtain real time readings of the controlled variables and the feedback loop was completed with predetermined nominal values [2]. The design offers high performance at rejecting ail and their experiments verify that the root-mean-square lateral displacement of the vehicle is very low as compared to 0.2 meters [2]. This control structure has a good theoretical strength and it is reliable when applied to linearized systems. When it comes its drawbacks, frequent over-conservative operation and online adjustment of control parameters remain invulnerable to tackle with.

3.2. Sliding-mode robust control

The sliding-mode control forces system states to slide on a predetermined sliding surface using discontinuous control laws, with full invariance to matched disturbances, making it one of the most well-developed robust control strategies available in robotics. Following an adaptive first-order sliding-mode backdrop estimator and two-phase composite sliding-mode control, Tao Yu and Zhixin Miao came up with a hybrid four-actuator configuration with a much shorter convergence time and better closed-loop stability [3]. The superior plans are terminal sliding mode, non-singular sliding mode, high-order sliding mode, and dynamic sliding mode. Common examples are force-position control, fault tolerant control and disturbance rejection of collaborative robots. It is responsive, robust, and easy to implement; however, it is prone to chattering effects with little ability to manage mismatched interference.

3.3. Robust model predictive control

The robust model predictive control (RMPC) incorporates model predictive control and robust invariant sets, Tube-MPC, and distributed MPC to directly address constraints and disturbances at the level of optimization. Juanjuan Zhang, Hexiang Yuan, and Jianda Han obtained approximate convex sets in a simplified form by clustering constraint distributions and constraining the system error to a given range, creating tractable constraint sets [4]. The sparse processing minimized the number of spatial parameters of robust invariant sets, which sharply decreased the computational complexity and enhanced the control precision and responsiveness. Example applications are mobile robot obstacle avoidance, formation control and safety constraints on human-robot interaction.

3.4. Adaptive robust control

Adaptive robust control combines online adaptive estimation of parameters and robust control terms to counteract uncertainties and make them less dependent on previous knowledge of disturbance limits. It is possible to combine adaptive robust control with other robust algorithms to create more adaptive control structures that are more robust to the closed-loop system. Through the use of potential functions and the Lyapunov stability theory, Zhigang Yu, Yongliang Shen, and Zhongming Song suggested a robust control approach, which allowed to observe the model uncertainties in real time and to drive tracking errors to zero over time [5]. The control strategy has been extensively used in robotic systems under fluctuating working conditions, including manipulators with varying loads, rehabilitation exoskeleton, and legged robots with steady gait control.

3.5. Observer-based robust hybrid control

There is an adoption of disturbance observers, extended state observers, nonlinear observers to estimate disturbances online and perform feed forward compensation which significantly decreases the necessary robust control gain and enhances control accuracy. The observers may be integrated together with various robust algorithms to create hybrid control architectures that improve performance of disturbance rejection. Common areas of use are precision assembly operations, high-speed movement applications, and fault detection modules of robots. Junfeng Wu et al. studied the stability of H 2 /H 1 full-dimensional state proportional-integral observers in the presence of time-varying conditions based on the theory of robust control [6]. They have obtained a list of sufficient requirements and applied them to calculate critical measures of performance such as steady-state proportional gains and other important parameters [6]. These enhancements are very effective in improving the total stability of the closed-loop system.

4. Applications of robust control in typical robotic systems

4.1. Collaborative robots

The collaborative robots are light-weight multi-DOF robotic systems intended to be operated by humans alongside with the robots, boasting fundamental requirements of safety, compliance, accuracy and excellent environmental versatility. Strong control guarantees stability and meets the required performance specifications when working with inaccurate models, parameter changes and external perturbations, which makes it one of the main technologies in mitigating uncertainty in collaborative robots. Using the rigid-body dynamics framework, Xindong Shu et al. developed both adaptive feed forward controller and adaptive-jerk robust integral control to remove modal interference caused by joint flexibility [7]. The core requirements are human-robot safety, force-position compliance, high disturbance rejection and fault tolerance. The popular schemes are robust impedance control and adaptive sliding-mode control and hybrid control based on disturbance observer. It is used in precision assembly, flexible grasping, and human-robot cooperative manufacturing.

4.2. Mobile robots

When deployed in unstructured environments, mobile robots often have inaccurate dynamical models, experience a wide range of complex external disturbances, motion parameters disturbances, and unpredictable conditions of the terrain. Traditional control techniques are unable to provide the accuracy of the trajectory tracking and the stability of the motion. Strong control is capable of maintaining stability and performance despite the presence of model errors, disturbances, and parameter changes acting as a fundamental technology that can be used to improve the environmental responsiveness and reliability of movements. Sliding mode control, H∞ control and adaptive robust control are representative robust algorithms that successfully dampen ground slip, load variation, sensor noise and external disturbance, with significant enhancement in positioning accuracy, tracking capability and safety during operation. According to the Lipschitz continuity of the disturbance rate and set-membership estimation, Chunyang Sheng et al. proposed a constrained MPC structure that provided both high precision and strong ability to follow the trajectory in the presence of external disturbances [8].

4.3. Legged/humanoid robots

Under the circumstance of working in heavy loads, rough terrains, and high model uncertainties, legged robots use H∞ and sliding mode robust algorithms to improve coherence and body stability, which mitigates the effect of load fluctuations, terrain perturbations, and model errors to achieve tracking precision and system robustness. Tianyu Wang et al. discussed the characteristics of systems and developed mathematical models, using an extended H∞ mixed sensitivity design, to directly solve the problem of low tracking accuracy of a single joint electro-hydraulic servo system applied to energy-efficient heavy-duty legged robots [9]. The mainstream methods are full-body robust control, robust MPC, and reinforcement learning with robust compensation.

4.4. Space/special robots

Robust control-based space robots are generally made to perform on-orbit capture, extravehicular activity, and servicing of spacecraft. To address model uncertainties, external influences, the base floating, manipulator flexibility and state constraints in the microgravity region, more sophisticated methods like H 8 control, sliding-mode robust control, finite-time robust control and command-filtered backstepping robust control are implemented to achieve better stability and tracking accuracy despite uncertainties. Finite-time command-filtered backstepping robust strategy was proposed by Xinwei Zhang et al., which solves the problem of trajectory tracking and performance constraint of space robots [10]. The main requirements stay zero-gravity disturbance rejection, actuator limits, high-reliability and fault-tolerant control. On-orbit manipulation, cabin operations, and extreme environment exploration lead the advanced technology application.

5. Existing challenges in current research

Nevertheless, at the moment, a number of practical technical challenges that hinder the use of robust control in robotics do exist. The disturbance modeling is badly conservative, where most of the techniques consider fixed bounded or norm-constrained disturbances, which do not adequately represent actual disturbances, and can result in overdesigned control gains and poor dynamic behavior. Engineering deployment is not supported by computational real time performance:

methods like robust MPC, high order sliding mode control, H -infinity synthesis require extensive online optimization and matrix computations, resulting in response latency and higher tracking errors in high dynamics systems. The multi-constraint compatibility remains insufficient: safety constraints, force control constraints, speed and torque constraints are hard to optimize equally and maintain robust performance. Experimental validation is disjointed: test conditions and metrics of evaluation differ between platforms, so it may have excellent simulation performance but poor generalization to actual robots making industrial translation difficult. Also, mutual management of faults and disturbances is not very effective: the majority of the available methods are developed to address one anomaly. If sensor drift, actuator failures, and external disturbances happen concurrently, the stability and tracking capabilities of the system are greatly reduced.

6. Conclusion

This paper classifies and discusses five representative robust control strategies of robots in a systematic manner, explain the principles of operation, methods of improvement, advantages and disadvantages of every strategy and summarize the effects of implementation into typical robotic systems. The analysis findings indicate that robust control has come up with a full theoretical framework and engineering implementation paradigm when it comes to model uncertainties, external disturbances, and actuator faults. This paper gives a good guideline to researchers and engineers on how to choose and develop robust controllers that are applicable to particular robotic functions, and enables standardization and engineering translation of robust control algorithms.

The results have great theoretical importance as well as practical relevance to enhance the stability, accuracy, and dependability of robots that work in highly unstructured environments. Future robotic robust control will be developed into greater precision, lighter implementation, increased intelligence, and increased integration. The researchers will be interested in building more precise complex disturbance models, lightweight robust control algorithms, multiconstraint cooperative optimization theory, unified robust control framework construction, collaboration with digital twin and multi-source perception, and standardized experimental verification protocol establishment to speed up industrial applications.

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