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*Editorial*

# Recent Progress in Robot Control Systems: Theory and Applications

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## 1. Introduction

Many engineering systems, such as electronic rotors, aircraft wings, and spacecraft flywheel structures, rely on the symmetry of their actuators. However, symmetry and asymmetry are not absolute in engineering science. Machining defects and external perturbations can introduce asymmetry to these controlled objects, compromising their performance and stability. Therefore, we need to design complex algorithms to preserve the symmetry of these elegant systems. Control system design is critical for the safe operation of various mechanical systems, such as space vehicles, maritime robotics, and micromechanical systems. Although current research has achieved remarkable results, there is still a high demand for more refined, intelligent, and low-resource-consumption technologies for control system algorithms to meet the industry's growth.

In this Special Issue, we collect original research and survey papers that reflect the recent advances in the theory and methodology of control system design and applications.

## 2. Noteworthy Aspects of the Special Issue

This Special Issue contains fifteen papers that cover the following aspects of recent progress in robot control systems: (1) Robotics Navigation and Control; (2) Aircraft/Spacecraft Systems; and (3) Reliable Designs. The following is a brief summary of the accepted papers. In addition, we will also present some other achievements that exist beyond this Special Issue. They will be included in Section 3.

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### *2.1. Robotic Systems*

Multi-line LiDAR and GPS/IMU are essential for autonomous driving and robotics such as SLAM. Multi-sensor fusion requires the calibration of each sensor's extrinsic parameters, which affect the vehicle's positioning control and perception performance. The algorithm obtains accurate extrinsic parameters and their confidence measures as a symmetric covariance matrix. Existing LiDAR-GPS/IMU calibration methods need specific vehicle motion or manual calibration scenes, leading to high costs and low automation. Ref. [1] proposes a new two-step self-calibration method: extrinsic parameter initialization and refinement. The initialization part decouples the rotation and translation parts of the extrinsic parameters and calculates the initial rotation by rotation constraints, and then the initial translation is calculated by a reliable initial rotation, and the LiDAR odometry drift is eliminated by loop closure to build the map. The refinement part obtains LiDAR odometry through scan-to-map registration and couples it tightly with the IMU. The absolute pose constraints in the map refine the extrinsic parameters.

In artificial intelligence, accomplishing emotion recognition in human–computer interaction is a key work. Expressions contain plentiful information about human emotion. Ref. [2] found that the canny edge detector can help to significantly improve facial expression recognition performance. A canny edge-detector-based dual-channel network using the OI-network and EI-net is proposed, which does not add redundant network layers and training. The method was verified in CK+, Fer2013, and RafDb datasets and achieved a good result.

Ref. [3] presents a novel algorithm for the industrial robot contouring control based on the NURBS (non-uniform rational B-spline) curve. Ref. [4] presents redundant posture optimization for 6R robotic milling based on a piecewise global optimization strategy considering stiffness, singularity, and joint limit.

To solve the problems of the poor exploration ability and convergence speed of traditional deep reinforcement learning in the navigation task of the patrol robot under indoor specified routes, an improved deep reinforcement learning algorithm based on Pan/Tilt/Zoom (PTZ) image information was proposed in ref. [5]. The obtained symmetric image information and target position information are taken as the input of the network, the speed of the robot is taken as the output of the next action, and the circular route with the boundary is taken as the test. The improved reward and punishment function is designed to improve the convergence speed of the algorithm and optimize the path so that the robot can plan a safer path while avoiding obstacles first. Compared with the Deep Q Network (DQN) algorithm, the convergence speed after improvement is shortened by about 40%, and the loss function is more stable.

Ref. [6] is entitled "Trajectory Tracking Control for Underactuated USV with Prescribed Performance and Input Quantization".

### 2.2. Aircraft/Space Vehicle Systems

Ref. [7] takes autonomous exploration in unknown environments on a small co-axial twin-rotor unmanned aerial vehicle (UAV) platform as the task. The study of fully autonomous positioning in unknown environments and navigation systems without global navigation satellite systems (GNSS) and other auxiliary positioning means is carried out. Algorithms that are based on the machine vision/proximity detection/inertial measurement unit, namely the combined navigation algorithm and the indoor simultaneous location and mapping (SLAM) algorithm, are not only designed theoretically but also realized and verified in real surroundings. Additionally, obstacle detection, the decision-making of avoidance motion, and motion planning methods such as Octree are also proposed, which are characterized by randomness and symmetry.

In response to the problems of slow running speed and high error rates of traditional flight conflict detection algorithms, Ref. [8] proposes a conflict detection algorithm based on the use of a relevance vector machine. A set of symmetrical historical flight data was used as the training set of the model, and they used the SMOTE resampling method to optimize the training set. They obtained relatively symmetrical training data and trained it with the relevance vector machine, improving the kernels through an intelligent algorithm.

According to the symmetrical characteristics of a new type of Reusable Launch Vehicle (RLV) in the recovery phase, [9] studied the basic aerodynamic model data of Starship and the aerodynamic data with rudder deflection, and the causes of its aerodynamic coefficients are expounded. They analyzed its stability and maneuverability. According to the flying quality requirements, the lateral–directional model of Starship in the return phase at a high angle of attack is analyzed. Finally, they analyzed Starship's lateral heading stability and control deviation using the criterion and nonlinear open-loop simulations. The results show that the Starship has pitching and rolling stability, but it only has heading stability in some ranges of angle of attack, and there is no heading stability at a conventional large angle of attack. After the modal analysis and comparison of flight quality, the longitudinal long-period model of the starship degenerates into a real root and it is stable and convergent. The lateral heading roll mode is at level 2 flight quality, the helical mode is at level 1 flight quality, and the Dutch roll mode diverges, which needs to be stabilized and controlled later.

Ref. [10] is entitled "Thrust Vectoring Vertical/Short Takeoff and Landing Aircraft Stability Augmentation Controller Based on L1 Adaptive Control Law". Aiming at the conversion process of thrust vectoring vertical/short takeoff and landing (V/STOL) aircraft with a symmetrical structure in the transition stage of takeoff and landing, there is a problem with the coupling and redundancy of the control quantities. To solve this problem, a corresponding inner loop stabilization controller and control distribution strategy are designed. In this paper, a dynamic system model and a dynamic model are established. Based on the outer loop adopting the conventional nonlinear dynamic inverse control, an L1 adaptive controller is designed based on the model as the inner loop stabilization control to compensate for the mismatch and uncertainty in the system. The key feature of the L1 adaptive control architecture is ensuring robustness in the presence of fast adaptation, to achieve a unified performance boundary in transient and steady-state operations, thus eliminating the need for adaptive rate gain scheduling.

A new landing strategy is presented in ref. [11] for manned electric vertical takeoff and landing (eVTOL) vehicles, using a roll maneuver to obtain a trajectory in the horizontal plane. This strategy rejects the altitude surging in the landing process, which is the fatal drawback of the conventional jumping strategy. The strategy leads to a smoother transition from the wing-borne mode to the thrust-borne mode, and has a higher energy efficiency, meaning a better flight experience and higher economic performance. To employ the strategy, a five-stage maneuver is designed using the lateral maneuver instead of longitudinal climbing. Additionally, a control system based on L1 adaptive control theory is designed to assist manned driving or execute flight missions independently, consisting of the guidance logic, stability augmentation system, and flight management unit. The strategy is verified with the ET120 platform by Monte Carlo simulation for robustness and safety performance, and an experiment was performed to compare the benefits with conventional landing strategies. The results show that the performance of the control system is robust enough to reduce perturbation by at least 20% in all modeling parameters, and ensures consistent dynamic characteristics between different flight modes. Additionally, the strategy successfully avoids climbing during the landing process with a smooth trajectory and reduces the energy consumed for landing by 64%.

### 2.3. Reliable Designs

Deep-learning-based methods have been widely used in fault diagnosis to improve diagnosis efficiency and intelligence. However, most schemes require a great deal of labeled data and many iterations for training parameters. They suffer from low accuracy and overfitting under the few-shot scenario. In addition, many parameters in the model consume high computing resources, which is far from practical. In ref. [12], a multi-scale and lightweight Siamese network architecture is proposed for fault diagnosis with few samples. The architecture proposed contains two main modules. The first part implements the feature vector extraction of sample pairs. It is composed of two lightweight convolutional networks with symmetrical shared weights. Multi-scale convolutional kernels and dimensionality reduction are used in these two symmetric networks to improve feature extraction and reduce the total number of model parameters. The second part takes charge of calculating the similarity of two feature vectors to achieve fault classification. Multiple datasets with different loads and speeds validate the proposed network. The results show that the model has better accuracy, fewer model parameters, and a scale compared to the baseline approach through our experiments.

Ref. [13] is entitled "Velocity-Free State Feedback Fault-Tolerant Control for Satellites with Actuator and Sensor Faults", Ref. [14] is "Finite-Time Controllers for Flexible Satellite Attitude Fast and Large-Angle Maneuver", and ref. [15] is "Fault-Diagnosis Sensor Selection for Fuel Cell Stack Systems Combining an Analytic Hierarchy Process with the Technique Order Performance Similarity Ideal Solution Method".

## 3. Exploring Further Advances in Intelligent Robot Control

Furthermore, we are pleased to introduce several noteworthy recent studies for scholarly consideration. While they may not comprehensively showcase all the achievements in robot control, they each possess certain commendable attributes.

### 3.1. Spacecraft Robot Control

Results in the control of spacecraft and robots: Ref. [16] proposes a control Lyapunov-barrier function-based controller for the stabilization of the spacecraft attitude tracking error system by combining a designed control barrier function and an existing control Lyapunov function. Ref. [17] investigates the distributed predefined-time attitude coordination control problem for multiple rigid spacecraft. Ref. [18] investigates the trajectory tracking control for a new type of cable-driven large space manipulator via sliding mode control techniques.

### 3.2. Control of Switching Systems

Results in the stability analysis and controller design of switching systems based on matrix equations: Refs. [19,20] propose an explicit iterative algorithm and an implicit iterative algorithm for solving the coupled Lyapunov matrix equation related to the stability analysis of continuous-time Markovian jump linear systems, respectively. Ref. [21] develops some convergence conditions for the multiple tuning parameters iterative algorithm and the single tuning parameter iterative algorithm, which is proposed to solve the discrete periodic Lyapunov matrix equations related to the control design of discrete-time linear periodic systems.

### 3.3. Self-Learning Control: A Simple and Effective Design

Self-learning control, originally referred to as online learning control, was initially proposed in [22], providing the first method for stability proof. Its most prominent attribute lies in its simple structure and practical applicability. In [22], it solely utilizes a straightforward proportional-derivative (PD) algorithm as the update term, complemented by a learning term with a fixed learning intensity. This approach achieves a remarkably high control precision and response speed while maintaining a simplified form of the control algorithm. In follow-up research [23], the authors further proposed a control algorithm with variable learning intensity to mitigate the controller saturation response. Additionally, in another investigation [24], the authors employed a variable learning intensity approach to enhance a learning observer, significantly reducing the initial transient oscillations during state and parameter estimation. Due to its user-friendly simplicity, the self-learning control method was swiftly applied to gyroscope systems [25], attaining state-of-the-art performance in certain metrics of gyroscope control systems.

### 3.4. State Estimation of Robotic Systems

Accurately retrieving information about the condition of a control system, particularly within the domain of aircraft and robotics, necessitates the utilization of state estimation as a highly effective approach for minimizing noise influence. In [26,27], the employment of FIR-smoothing methods has resulted in notable enhancements in estimation performance concerning observation data that exhibit time delays. Additionally, the destabilizing effects of faulty signals on controller stability are estimated by leveraging the mean-field theory described in [28,29]. To fortify resistance against disturbances, the methods proposed in [30,31] leverage Bayesian inference to capture the inherent randomness of unknown signals. For the localization of the underground pipe jacking machine, [32] designed a reliable, real-time, and robust INS/OD solution.

### 3.5. Trends in Control Systems for Micro Gyroscopes

Another notable trend would be focused on micro-electro-mechanical (MEMS) gyroscopes, which are an essential inertial sensor for robotic navigation and attitude control [33]. They may be considered to be black-boxed sensors within the field of robotics, but they are inherently complicated and self-sustained closed loop control systems [25]. By examining the operation principles, it can be found that there are typically more than four control loops in a single working MEMS gyro chip. The control plant would be a pair of orthogonal resonators coupled with the Coriolis effect along with frequency tracking, amplitude adjustment, quadrature nulling, and force-to-rebalance controllers [34]. Improving the fabrication quality of gyro devices is a straightforward way to enhance the sensing metrics, but optimizing control systems is the advanced approach to break the performance barrier [35]. By switching empirical controller designs to model-based force-to-rebalance controllers, the bandwidth can be magnified by 5×~10× [36]. Self-calibration architectures that observe the gyro parametric errors and calibrations made using electrical stimulus are another implementation of advanced control systems [37], whether they are acknowledged by the MEMS designers or not. In any case, advanced control systems will play an essential role in the field of inertial sensors.

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