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EDITORIAL

IEEE ACCESS SPECIAL SECTION EDITORIAL: ADVANCED MODELING AND CONTROL OF COMPLEX MECHATRONIC SYSTEMS WITH NONLINEARITY AND UNCERTAINTY

Various complex mechatronic systems are widely applied in industries such as robotics, micro-electro-mechanical systems (MEMS), and motor or hydraulic-driven equipment, and control technology is one of the key issues for mechatronic systems to achieve the desired high performance. However, for those complex mechatronic systems, mechanism nonlinearities and uncertainties (e.g., internal uncertainties, external unstructured environments, and undesired disturbances) are much more obvious and bring significant negative effects. Thus, effective modeling, identification, and dynamic analysis are necessary for complex mechatronic systems with nonlinearity and uncertainty. Model-based advanced control designs, such as adaptive control, robust control, sliding-mode control, backstepping control, and H-infinite control, are the corresponding solutions to improve system performance. Advanced modeling and control is one of the key points in industries for those complex mechatronic systems, where nonlinearity and uncertainty become more and more challenging to pursue higher system performance. The topic of this Special Section in IEEE ACCESS is mainly focused on the categories of control systems, robotics, and automation and also covers other categories such as systems, man, and cybernetics, industrial electronics, and mechanical engineering. We received a total of 104 submissions, and after a rigorous review process, 29 articles have been selected for publication, which are briefly discussed next.

In the article ''Ship adaptive course keeping control with nonlinear disturbance observer,'' Liu investigated a scheme to reject the unknown, bounded, time-varying external disturbance for a ship course-keeping control system. A mathematical model of a steering system was derived, and the feedback linearization approach was adopted to simplify the nonlinear system. Furthermore, the adaptive sliding mode control algorithm and nonlinear disturbance observer method were developed. The simulation results illustrated the effectiveness of the proposed controller on a navy vessel with twin rudders.

The dynamic model of a doubly fed induction generator (DFIG)-based wind energy system is subjected to nonlinear dynamics, uncertainties, and external disturbances. In order to deal with such nonlinear effects, in the article ''Adaptive fractional order terminal sliding mode control of doubly fed induction generator based wind energy system,'' Ullah *et al.* proposed a novel fractional-order adaptive terminal sliding mode control system for both the rotor and grid side converters of the DFIG system. The stability of the closed loop was ensured theoretically, and the numerical results showed superiority over the classical sliding mode control system and the PI controllers.

In the article ''Finite-state model predictive current control for surface-mounted permanent magnet synchronous motors based on current locus,'' Su *et al.* proposed a novel finite-state model-based predictive current control (MPCC) scheme, to overcome the computational drawbacks of conventional finite-state model predictive control (FS-MPC). Based on the prediction of the current locus, a reference frame was established to reduce the computational requirements, and specifically, only one zero-voltage vector must be predicted compared with the seven required in FS-MPC. Both simulation and experimental results were presented to show the improvement of computational efficiency of the proposed MPCC.

In the article ''A novel control strategy for an interior permanent magnet synchronous machine of a hybrid hydraulic excavator,'' Chen *et al.* investigated the implementation of an interior permanent magnet synchronous machine (IPMSM) in the hybrid hydraulic excavator. Based on the analyses of the mutual influence between the torque of the IPMSM and the direct current (dc) voltage, a novel high-performance control strategy for the IPMSM was proposed to improve its torque controllability and to make it insensitive to the influence from DC voltage. Both the simulations and experiments were conducted and the results showed the improvement of the control performance of the IPMSM.

In the article "Composite controller for antagonistic tendon driven joints with elastic tendons and its experimental verification," Shoaib *et al.* presented the dynamic modeling and controller design of a tendon-driven system that was antagonistically driven by elastic tendons. The tendons were approximated as linear axial springs in the dynamics modeling, and overall equations for the motion were established, combining both rigid-body rotation and vibration. The composite controller was designed based on the singular perturbation approach. Experiments were conducted to demonstrate the validity and effectiveness of the proposed controller.

The article titled "Quantized adaptive decentralized control for a class of interconnected nonlinear systems with hysteretic actuators faults," by Khan *et al.*, proposed a quantized adaptive decentralized output feedback control approach for a class of interconnected nonlinear systems with quantized input and possible number of hysteretic actuators failure up to infinity. The hysteretic actuators nonlinearities were described by the Prandtl–Ishlinskii model first, and then a modified backstepping approach was proposed by utilizing the high-gain k-filters, hyperbolic tangent function property, and bound estimation approach. It was proved both mathematically and by numerical simulations that all the signals of the closed-loop system could be bounded globally.

A comprehensive analysis of how to stabilize an urban, semi-autonomous bicycle was carried out in the article by García *et al.*, titled "Stabilizing an urban semi-autonomous bicycle." The study of bicycle dynamics and stability control led this investigation. Consecutively, all the examined aspects were applied to introduce a few alternatives to solve the stability problem. One of them, the Alnilam concept, was further developed to unveil its possibilities. Such a concept had been successfully tested in a multibody cosimulation using Adams and Simulink, illustrating its behavior and testing its performance.

The supply pressure control problem was studied for a self-supplied variable displacement axial piston pump, in the article by Guo *et al.*, titled "A switched controller design for supply pressure tracking of variable displacement axial piston pumps." Due to the supply mechanism of the pump, the mathematical model demonstrated a switching characteristic. In addition, one of the two subsystems was nonminimum phase, which complicated the control design. Therefore, a control strategy, which used the method of output redefinition combined with a switching control scheme, was proposed. The stability of the overall system was guaranteed as well as the bounded tracking error. The experiments were carried out to illustrate the effectiveness of the proposed controller.

In the article "Speech enhancement based on NMF under electric vehicle noise condition," by Wang *et al.*, a speech enhancement method based on improved nonnegative matrix factorization (ImNMF) was proposed. Unlike the traditional NMF, the ImNMF generated the speech dictionary using the spectra of pitch and their harmonics via a mathematical model, which could guarantee the purity of the dictionary. To alleviate the loss of the information of the noise sample, the ImNMF constructed a noise dictionary by a combination of the gain-adjusted spectrum frames of the noise samples separated online. The experiments showed that the proposed ImNMF can effectively enhance speech signals in the noise environment of electric vehicles.

To deal with the influence of the characteristic of the inner current loop in high-velocity/high-precision linear motion systems, the article by Yang *et al.*, titled "Robust predictive current control with variable-gain adaptive disturbance observer for PMLSM," proposed an online adaptation-gain update method that can extend the inductance robust limit. An adaptive disturbance observer was introduced to eliminate the static current errors first, and then an improved variable-gain method utilizing the current estimation errors was developed to reduce the current overshoot and the oscillation. Finally, the effectiveness of the proposed method was uniformly verified with both simulation and experimental results.

The article by Sun *et al.*, titled "Nonlinear motion control of a hydraulic press based on an extended disturbance observer," focused on high-performance motion control of the electro-hydraulic system of hydraulic presses. To attenuate the effects of the nonlinearities, uncertainties, and disturbances, a nonlinear robust motion controller based on an extended disturbance observer was developed. The outer position tracking loop was designed with a sliding mode control to compensate for disturbance estimation error, while the inner pressure control loop using the backstepping method can realize accurate output force control. The simulation and experimental results illustrated the good transient-response and accurate position tracking performance.

To achieve high-performance motion control accuracy for complex contouring tasks even under high-speed and large-curvature, a generalized global task coordinate frame (GGTCF)-based learning adaptive robust control (LARC) strategy was synthesized for the industrial biaxial mechatronic stage systems, in the article by Hu *et al.*, titled "Generalized GTCF coordination mechanism based LARC contouring control of industrial motion stages for complex contours." Specifically, GGTCF was first proposed and globally designed based on a synthesized equivalent shape function of the desired contour. Then, a LARC contouring controller was constructed for the strongly coupled nonlinearities in GGTCF to achieve great contouring motion performance. Comparative experiments under various complex contours were conducted on an industrial linear-motor-driven biaxial motion stage, and the results showed excellent transient/steady-state contouring control performance.

The article by Wang *et al.*, titled "Reliability-based performance optimization of tunnel boring machine considering geological uncertainties," focused on developing an effective method to optimize the performance (e.g., advance rate and energy consumption) of a tunnel boring machine (TBM) by determining reasonable operating and structural parameters according to geological conditions. The multidisciplinary modeling of the subsystems of the TBM was performed to derive the performance functions and limit state functions of the whole machine first, and then a reliability-based performance optimization strategy was developed by taking the stochastic properties of rocks into account. Case studies were conducted to validate the proposed method.

The article by Xia *et al.*, titled "Modeling and three-layer adaptive diving control of a cable-driven underwater parallel platform," focused on the modeling, diving controller design, and experiment of a special cable-driven underwater parallel platform with eight-cable coupling drive structure. The kinematic and dynamic models were established first, and then a three-layer adaptive diving control strategy was proposed to improve the diving control precision and system robustness, despite the complex dynamic behaviors and manifold unknown disturbances. Hardware-in-the-loop simulations and experimental results illustrated that the proposed control strategy can asymptotically drive the cable-driven underwater parallel platform onto a predefined diving trajectory with favorable precision, robustness, and stability.

In the article "A novel wave-variable based time-delay compensated four-channel control design for multilateral teleoperation system," by Chen *et al.*, a four-channel multilateral teleoperation control problem was discussed, where n masters controlled the n slaves to handle dangerous, unknown, and complicated tasks remotely under time-varying delays in the communication channel. A novel multilateral teleoperation system combining the time-delay compensator by the novel wave transform and four-channel architecture was built to meet the demands of the communication among multiple masters and slaves. The signal transmission was optimized and the stability guaranteed in the four-channel architecture, and ideal transparency conditions were theoretically derived to simultaneously achieve stability and good transparency performance. The practical experiments are carried out to verify the effectiveness of the proposed control scheme.

In order to reduce the overflowing energy loss of the relief valve, the article by Lin *et al.*, titled "A novel control strategy for an energy-saving hydraulic system with near-zero overflowing energy-loss," proposed a new type of proportional relief valve (PRV) with a hydraulic energy regeneration unit (HERU) connected to its outlet. A control strategy was put forward to design the working modes, which were based on the pressure of the hydraulic accumulator. A hydraulic accumulator was used as a HERU in the simulations and experiments. The results verified the effectiveness of the control strategy and energy savings of the proposed PRV.

Energy management strategies are widely used for the fuel efficiency of hybrid electric vehicle (HEV). In the article "Energy management strategy for Atkinson cycle engine based parallel hybrid electric vehicle," Asghar *et al.* tried to devise and demonstrate energy management strategy (EMS) by giving full consideration to the powertrain using the Atkinson cycle engine. A novel energy management strategy based on the vehicle speed for the Atkinson cycle engine for HEV was proposed. The simulation showed that the proposed EMS with Atkinson cycle engine control framework exhibited significant improvement in the fuel economy around 12.30% for standard Manhattan driving cycle and 7.22% for the modified federal urban driving schedule (FUDS) driving cycle in comparison with the Otto cycle engine.

In the article by Wang *et al.*, titled "Adaptive fuzzy sliding mode observer for cylinder mass flow estimation in SI engines," a novel algorithm for the cylinder mass flow estimation in four-stroke spark ignition (SI) gasoline engines was developed to improve the estimation precision under transient conditions. First, a fuzzy logic system (FLS) with three inputs was adopted to parameterize the volumetric efficiency error. Then, with the combination of the FLS and the gasoline engine air path system, an adaptive fuzzy sliding mode observer was presented to estimate the states and parameters jointly and suppress the disturbance from the FLS approximation error. The convergence of the proposed method was proven under certain conditions.

In the article by Chen, titled "Discrete-time adaptive control design for ionic polymer-metal composite actuators," a new mathematical model in discrete-time domain was proposed for IPMC actuator. Based on the obtained model, a discrete adaptive control law was synthesized for IPMC actuators. The proposed discrete adaptive controller could guarantee the global stability of the closed-loop system, and the position tracking error of the IPMC actuator could be controlled by the design parameters. Finally, the proposed model and control law were verified by IPMC actuator experiments.

To investigate the unknown (uncertain) tire steering resistance moment and model uncertainties in a multiaxle vehicle electro-hydraulic power steering system (EHPSS), an adaptive robust control algorithm was developed in the article by Du *et al.*, titled "Adaptive robust control of multi-axle vehicle electro-hydraulic power-steering system with uncertain tire steering resistance moment." The comparative simulation results demonstrated that the proposed adaptive robust control scheme could achieve the desired performance for feasible tracking trajectories despite the existence of an uncertain tire steering resistance moment and external disturbance in the EHPSS.

The article by Shi *et al.*, titled "Desired compensation nonlinear cascade control of high-response proportional solenoid valve based on reduced-order extended state observer," focused on the method to get a strong robustness and high-performance controller for the high-response proportional solenoid valve (HPSV). The reduced-order extended state observer (RESO) was proposed to estimate the unmeasured state variables and the lumped uncertainties first, and then a nonlinear cascade (NC) control-based RESO for HPSV was developed, which adopted the desired compensation method to reduce the influence of the measurement noise. The system stability and error boundedness was proved theoretically, and the experiments were conducted to verify the effectiveness of the proposed method.

The article by Ma *et al.*, titled "Continuous integral robust control of electro-hydraulic systems with modeling uncertainties," studied the high-performance tracking control of electrohydraulic systems with consideration of both mismatched and matched modeling uncertainties. A continuous integral robust control strategy was proposed based on the backstepping design framework. By introducing a novel error transformation, the mismatched modeling uncertainty could be transmitted to the control input channel, and then the constructed integral robust structure in the proposed controller could handle it together with the matched modeling uncertainty. The final control input was continuously differentiable, which would help improve the tracking performance and practical controller implementation. Comparative experiments were performed to demonstrate the effectiveness of the proposed control strategy.

In the article "μ-based theory in compliant force control for space docking," by Yu *et al.*, a compliant force control system based on the inner position loop of the six degree-of-freedom parallel robot was established first, and then the major characteristics of the system were studied. To get satisfactory system stability and force control characteristics, a robust controller was designed using the μ synthesis control theory, where the system parameter variation, the model change, the external interference, and the system bandwidth were synthetically considered. Both the simulations and experiments showed the effectiveness and superiority of the proposed controller over the classical one.

The article by Chen *et al.*, titled "Nonlinear dynamics modeling and analysis of underwater mud-penetrator steering system," established the kinematics model of the underwater mud-penetrator in the inertial coordinate system first. It then discussed the drill steering mechanism and force characteristics under the nonlinear coupling interaction between drill bit, drill pipe, and seabed geology. The nonlinear dynamic model of mud-penetrator was established, and the influence of guiding angle, geological features, and propelling force on a steering process were analyzed through simulation.

The article by Zhou *et al.*, titled "A robust control strategy research on PMSG-based WECS considering the uncertainties," proposed a robust control strategy for the uncertainties of a permanent magnet synchronous generator-based wind energy conversion system. Meanwhile, the detailed design and analysis process of this robust controller were presented. The proposed method could not only make the whole closed-loop system stable but also reduce the major harmonics and total harmonic distortion of currents and ripples of torque. The effectiveness of the proposed method was validated by simulation.

In the article "A novel position-based impedance control method for bionic legged robots' HDU," by Ba *et al.*, a novel impedance control method was designed by combining the stiffness control and the damping control for the hydraulic drive unit (HDU) equipped on the hydraulic- driven legged robot. The experiments were carried out and the impedance control effects were verified by comparing the impedance characteristics with the natural characteristics of the second-order mass-spring-damper system. The research provided references for the active compliance control of bionic legged robots.

The wave glider is a new-concept marine robot that can make use of wave energy to obtain thrust, but the conventional kinetic models of the unmanned vehicle are inapplicable for it. In the article "Dynamics modeling of a wave glider with optimal wing structure," Chen *et al.* proposed a nonlinear kinetic model of wave glider of six degrees of freedom based on three reference coordinate frames. On the basis of the static stress analysis of the Glider wings, the authors compared different factors influencing the advance speed and optimized them by comparing the simulation results with the calculation results.

In the article by Kim *et al.*, titled "Estimating water current velocities by using a model-based high-gain observer for an autonomous underwater vehicle," a high-gain observer based on an autonomous underwater vehicle (AUV) dynamics model was used to estimate 3-D water current velocities. This article presented a real-time model identification algorithm to identify the nonlinear parameters of the AUV model by utilizing a recursive least squares method, where a high-gain observer was chosen as the nonlinear estimation algorithm. The results showed that the performance of the current estimation with the proposed model-based observer was improved compared with the classical water current estimation method.

The article by Luo *et al.*, titled "Adaptive repetitive control of hydraulic load simulator with RISE feedback," was an invited article. The electro-hydraulic load simulator is a typical test-equipment for hardware-in-the-loop simulation and usually performs periodic tasks, in which the modeling uncertainties will also present some periodicity. With this notification, in this article, the system model of electro-hydraulic load simulator was established, and afterward, all periodic uncertainties were transformed into linear-in-parameters form by applying Fourier series approximation. Then, an adaptive repetitive scheme with a robust integral of the sign of the error (RISE) feedback was synthesized, in which adaptive repetitive law was designed to handle periodic uncertainties and RISE robust term to attenuate unmodeled disturbances. In comparison to the other three controllers, the effectiveness and high performance of the proposed control method were validated by the experimental results sufficiently.

To conclude, we would like to sincerely thank all the authors for submitting their articles to our Special Section, and the large number of reviewers who kindly volunteered their time and expertise to help us curate a high-quality Special Section on this important and timely topic. We would also like to thank the IEEE Access Editor-in-Chief and other staff members of IEEE Access for their continuous support and guidance. We hope that you enjoy reading the articles within this Special Section and that the published work is inspirational in contributing to the progression of the state of-the-art in modeling and control of mechatronic systems.

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