

Nonlinear Control of Mechanical and Robotic Systems

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Position and motion control of robotic and mechanical systems have proven to be challenging tasks, primarily because of their multidimensional, coupled and highly nonlinear dynamics. This, as well as the need for the system to move within a wide range of its motion domain, makes nonlinear control design a necessity. Probably the most popular and *ad hoc* design method for robotic and mechanical systems is *Passivity-Based Control* [1], which uses control laws that involve position- and velocity-error correction terms, as well as model-dependent terms, that render the desired trajectory/position as a closed-loop equilibrium; this is given adequate stability properties through the aforementioned correction terms shaping the potential energy function and injecting damping (*via* the position- and velocity-error related terms, respectively). In such a model, it is hard to imagine a robotic or mechanical system being controlled across a wide range of its motion domain without the system model being included in the control algorithm. But this adds further complications. The system's physical parameters are not always exactly known or could change over time. Moreover, there could be unmodeled phenomena; friction components and input saturation are common examples of this. The latter is a consequence of natural restrictions on actuator capabilities, but further constraints on the system's physical configuration or velocities could also need to be considered (velocities being relevant, for instance, in the case of mobile robots). Further complications include the lack of system variable (such as velocity) measurements or underactuation. On the other hand, high-accuracy closed-loop performance is now expected or even demanded. All these aspects have produced the need for refined control design, giving rise to nonlinear control schemes with sophisticated design techniques, such as adaptive [2], robust [3], output-feedback [4], bounded [5], or finite-time control [6], as well as combinations of these, such as robust adaptive [7], bounded output-feedback [8], bounded finite-time [9] or finite-time adaptive controllers [10]. Improvements on control design that take these complications into account are continual active topics in the research community.

This Special Issue collects works that present recent advances in nonlinear control of robotic and mechanical systems. It contains eight articles that deal with the above-mentioned active topics or with aspects that are intimately related to the control design, testing or implementation of such systems, such as modeling or design, construction, and actuation of robots with innovative mechanical structures. The included papers are briefly described below.

Contribution 1 develops an innovative view on handling (often neglected) Coulomb and viscous friction components in the control of robot manipulators. Considering them as additive dissipative disturbance terms with a known linearly parameterizable structure



Received: 17 July 2026

Accepted: 23 July 2026

Published: 29 July 2026

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that proves to be *ad hoc* for control design purposes, the authors successfully design a composite adaptive control scheme that achieves trajectory tracking and, under persistently exciting desired trajectories, estimation of system and friction component parameters. Such an approach contributes a practical control strategy for refined trajectory tracking of robot manipulators. A thorough Lyapunov-function-based closed-loop analysis supports the contributed design, and experimental results on a two-degree-of-freedom robot arm further corroborate the analytical results and the efficiency of the proposed control scheme.

Contribution 2 presents a novel strategy for the validation of nonlinear robotic control systems prior to implementation. The proposed strategy combines Hardware-in-the-Loop (HIL) and Digital Twin (DT) technologies. HIL is described by the authors as a novel testing methodology used within the field of control system development, enhancing interaction between hardware components and simulated or emulated environments. DT is described by the authors as a virtual representation or model of a physical object or process obtained from real-world data. The authors show the efficiency of their proposed methodology through an experimental implementation of a development environment for the nonlinear trajectory tracking of a wheeled differential drive device: the P3-DX robot. The implementation involves a Lyapunov-based designed controller.

Contribution 3 details an optimal control scheme for autonomous vehicles navigating intersection scenarios. The control design is based on the solution of a Quadratic Programming optimization technique. Compared to previous approaches, this work presents a low-level control system that only involves on-board sensors and computers to accurately navigate intersections, avoiding communication between agents and external sensing. The control scheme is supported through a Lyapunov-based closed-loop analysis and experiments on an AutoMiny platform. The proposed control approach further deals with input constraints, solving the tracking problem and avoiding input saturation.

Contribution 4 gives an integral solution to the open challenge of achieving trajectory control for autonomous car-like mobile robots. It solves this complex problem through a modular system that incorporates a multi-level hierarchical control scheme. The modular scheme combines an extended Kalman filter for state estimation, frugal model predictive control for trajectory tracking, and an electronic differential through which each wheel is independently regulated by a nonlinear dynamic control law capable of addressing model uncertainties and external disturbances. The study includes all the analytical details, as well as experimental validation through a simple yet complete experimental platform using open and standardized communication protocols, an on-board embedded system to drive wheel angular velocities and direction, and a MATLAB-ROS (Robot Operating System) 2024B ground station. The experimental results demonstrate that the interval disturbance-compensating low-level control, predictive high-level planning, and sensor-fusion-based state estimation provide an effective solution for reliable autonomous navigation in challenging environments.

Contribution 5 presents the design and implementation of a novel tendon-driven manipulator motivated by weight reduction and increased flexibility for rigid-link manipulators. The study not only covers the technical details of the design but also produces a kinematic model. It further develops a non-singular terminal-sliding-mode control scheme with time-delay estimation by using the weighted average of estimated unknown dynamics at two different delay times. Such a control design is supported through Lyapunov analysis. Through experimental implementation, the constructed prototype is proven to offer reliable performance. The presented study on the implemented prototype thus shows its feasibility for applications, offering advantages in weight reduction, drag minimization and control implementations.

Contribution 6 deals with the control of unmanned surface vehicles (USVs) under model uncertainties, unknown parameters, and external disturbances. The proposed approach engages with the underactuated nature of USV dynamics through a suitable change of coordinates. Since the transformed system dynamics involve hydrodynamic coefficients, which are very difficult to determine, the authors include a novel sliding-mode-based dynamic neural network identifier that enables the reconstruction of the transformed coordinates without the need for exact values of the system parameters. Moreover, the design leads to finite-time convergence of the defined sliding-surface variable and errors in the neural weights to zero in finite time. The convergence of the transformed coordinate reconstruction errors is proven to take place asymptotically. The estimated transformed coordinate variables are then transmitted to a sliding-mode-based controller that guides those variables to the desired trajectory. The analysis is supported through Lyapunov-based analysis and corroborated through simulation results.

Contribution 7 presents the design and modeling of a new robotic device constructed to assist therapists in the rehabilitation of sit-to-stand and walking movements. The paper focuses on the technical aspects of the system and provides a detailed mathematical analysis of its mechanics. The development of the designed prototype is described, covering the main aspects considered during the mechanical design, the definition of the control architecture, and the integration of the system components. The paper covers all the details of the inverse-kinematics and -dynamics models. It further highlights the usefulness of these models to address crucial aspects such as the determination of the required position and velocity profiles, providing necessary tools for the control of the robot and the design of the mechanical architecture of the prototype.

Contribution 8 focuses on the validation of pneumatic actuation for fast fatigue testing of additively manufactured polymers. Through mechanical testing machines equipped with control systems, the work validates pneumatic actuators as a viable alternative to servo-hydraulic systems, showing their effectiveness and reliability. This is significant for the robotics community, as the growing interest in compliant and soft robotics has prompted researchers to reconsider the potential of pneumatic actuation for advanced and complex applications.

We believe that the above-described works included in this Special Issue present relevant contributions to the research community on the control, modeling, design, implementation and actuation of robotic and mechanical systems. We are convinced that scholars, researchers and readers interested in the treated topics will find appealing original solutions to interesting open problems in this collection. Future research should focus on the integration of further constraints into control design. For instance, input constraints are not always considered, or their impact may be evaluated through implementation tests that are not necessarily exhaustive. While further integration of these and other types of constraints into control design has not been exhaustively studied for all types of mechanical systems—or is often disregarded in the formulation of considered problems—it has proven to be the only way to ensure avoidance of the potentially undesirable or unexpected effects that result from their omission. We thank all the reviewers involved in reviewing the accepted papers, as well as all the personnel from *Actuators* for their invaluable help in the production of this Special Issue.

Author Contributions: Conceptualization, A.Z.-R., V.S. and F.R.-C.; methodology, A.Z.-R., V.S. and F.R.-C.; investigation, A.Z.-R., V.S. and F.R.-C.; writing original draft preparation, A.Z.-R., V.S. and F.R.-C.; writing review and editing, A.Z.-R., V.S. and F.R.-C.; visualization, A.Z.-R., V.S. and F.R.-C.; supervision, A.Z.-R. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declares no conflicts of interest.

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