Guest Editorial: Special Issue on State-of-the-art Applications of Model Predictive Control

I. Introduction

Advancements in computing hardware and refinements of numerical solvers for convex optimization problems have prompted a burst of interest in the utilization of model predictive control (MPC) to a myriad challenging control problems and scenarios. Undoubtedly, the tremendous success enjoyed by model-predictive controllers across a wide variety of industrial and technological settings is ascribable to the potential for optimizing performance while guaranteeing the satisfaction of system constraints via recursive online optimization. This unique capability represents a most appealing feature in contexts where autonomy, safety, reliability, flexibility and cost-effectiveness are important or essential requirements.

Fueled by the growing success of MPC as a powerful and versatile tool, both in traditional and unconventional control domains, this special issue aims at providing a comprehensive snapshot of the state-of-the-art of advanced applications of model predictive control. On the one hand, emphasis has been given to highlighting the benefits provided by the MPC techniques within the context of a given technological problem; on the other hand, to unveiling the challenges encountered when implementing novel theoretical findings in problems with stringent performance specifications and constraints. Within the special issue, the reader will be presented with demanding applications where different MPC techniques have been developed or tailored to achieve the required objectives while abiding by available computational resources. The articles present developments in MPC design and practice, driven by the specific needs of established and emerging applications.

II. Issue at a Glance

The aim of this special issue is to establish a connection between recent theoretical advancements in predictive controls and their practical implementation in various application areas. After issuing a call for papers, we received a total of 49 full paper submissions. Through a meticulous peer review process, we carefully selected 24 manuscripts to feature in this special issue. The selected papers encompass a wide array of subjects, all focused on utilizing diverse MPC techniques, including nonlinear, economic, and stochastic MPC schemes. The accepted papers were then organized by application domains into eight main categories: aerospace systems, autonomous driving, marine systems, electric mobility, smart grid, sustainability, smart infrastructure, and healthcare.

A. Aerospace Systems

The first three papers focus on aeronautical and space applications, mainly proposing different MPC-based control strategies for trajectory tracking. In Quartullo *et al.*, a periodic MPC approach is developed for tracking halo orbits in the elliptic restricted three-body problem. The control design utilizes eccentricity continuation techniques, exploits periodicity, and ensures stability and fuel efficiency, validated through simulations in the Earth-Moon system. The other two papers focus on unmanned aerial vehicles (UAV). In particular, Saccani *et al.* propose a multi-trajectory MPC (mt-MPC) for navigating a UAV in an unknown environment. Using limited sensor information, it focuses on safely driving the vehicle to a target location. The mt-MPC scheme generates a sequence of position setpoints by predicting two different state trajectories: a safe trajectory and an exploiting trajectory. This approach allows for handling time-varying constraints and decoupling constraint satisfaction from cost function minimization. Uncertainty from modelling errors and sensor noise is considered within a set membership framework. Theoretical guarantees for persistent obstacle avoidance are derived, and the approach is experimentally validated on a prototype UAV constructed with off-the-shelf components. In Dong *et al.*, a novel approach to track a moving target along a circular path with a UAV is proposed. It uses a Lyapunov guidance vector field and a deep neural network (DNN)-based model predictive control scheme. The method involves offline training of the DNN and includes an integral module for improved tracking. Hardware-in-the-loop simulation demonstrates the feasibility of the proposed method as an alternative to embedded MPC implementations for complex systems and applications.

B. Autonomous Driving

Autonomous driving refers to self-driving vehicles or transportation systems that operate without the intervention of a human driver. In this category, five papers address the challenges of the application field. Pan *et al.* present a hierarchical robust control strategy for cooperative vehicle management at signal-free intersections. This paper addresses uncertainties in vehicle model and sensor measurements and focuses on optimizing energy consumption and throughput. The approach formulates the optimization problems as convex second-order cone programs which admit computationally efficient solutions. Simulation results validate the effectiveness and robustness of the strategy, emphasizing the trade-off between energy consumption and journey time. Numerical comparisons are conducted for different prediction horizons and sampling intervals, offering further insights into the control design. In Batkovic *et al.*, an MPC framework for autonomous driving systems is proposed, ensuring provably safe operation. It guarantees constraint satisfaction and tracks reference trajectories while considering obstacles. The effectiveness of the proposed scheme is demonstrated through simulations and real test vehicle experiments. An agricultural application is presented in Soitinaho *et al.*, where a nonlinear model predictive control (NMPC) approach for automating agricultural vehicle navigation is proposed. The NMPC utilizes a kinematic model, penalizes cross-track error and obstacle proximity, and achieves accurate path tracking and obstacle avoidance. Simulation and real-life experiments validate the effectiveness of the controller, demonstrating its feasibility for real-time field applications. Autonomous racing is the target application of the following two papers. In Picotti *et al.*, a learning-based NMPC approach for autonomous driving is described, which utilizes Gaussian processes and system data to develop a continuous black-box model for control. The effectiveness of the approach is demonstrated through testing on a real go-kart vehicle, highlighting the required approximation steps for real-time applications. Knaup *et al.* focus on autonomous racing in uncertain off-road environments. The authors develop a stochastic model predictive controller (SMPC) based on optimal covariance steering (CS) theory. The proposed CS-SMPC algorithm effectively handles uncertainty and ensures stability, demonstrated through numerical and experimental tests on scaled and full-size racing platforms.

C. Marine Systems

The category of marine systems includes both unmanned and manned systems, where in the latter, a certain control functionality may be characterized as autonomous. This is the case of the first paper by Zhang *et al.*, which presents a control scheme for launching and recovering lifeboats from a mother ship, featuring risk assessment and two-stage control. A robust model predictive control law considers uncertainties and guarantees constraint satisfaction, improving safety. Performance is demonstrated through numerical simulations. In Du *et al.*, a distributed dynamic coordination control scheme is proposed for a multi-vessel autonomous towing system to transport an offshore platform. The scheme uses a multilayer MPC strategy and a distributed control architecture based on the Alternating Direction Method of Multipliers (ADMMs). Simulation results demonstrate efficient transportation of the platform under environmental disturbances.

D. Electric Mobility

Electric mobility comprises all vehicles that are propelled by electric motors, with the electrical power grid as their primary source of energy. Two papers are included in this category, one devoted to railway systems with catenary grids, and the other to thermal management in electric vehicles. In particular, in Incremona *et al.*, a novel approach for collaborative train control in railway systems is presented. It minimizes traction energy and power line losses by combining train dynamics and catenary grid models. The proposed eco-drive control system, based on switching nonlinear model predictive control, outperforms non-collaborative methods in terms of energy efficiency. Simulation case studies using real-world data validate the effectiveness of the approach and highlight its potential positive impact on railway systems with catenary grids. Hu *et al.* focus on minimizing energy consumption in the thermal management system of electric vehicles. The work employs a model predictive controller that considers power and thermal constraints. The strategy captures the dynamics of the powertrain and thermal subsystems, incorporating long prediction horizons and addressing uncertainties. Real-world traffic data and location-dependent constraints are utilized to improve robustness and energy efficiency. Simulation results validate the effectiveness of the approach.

E. Smart Grid

This category involves three papers devoted to the control of power grids and the optimization of energy allocation in a variety of scenarios. Sivianes *et al.* propose a stochastic programming method to control a residential microgrid using model predictive controllers in a hierarchical and distributed scheme. A smart contract written into a blockchain coordinates control tasks, while individual agents optimize local control. Simulations demonstrate the approach's performance in different power-trading configurations. Dkhili *et al.* address the challenges posed by integrating renewable-energy-based power generation into power grids. It proposes a model-based predictive controller that incorporates the stochastic nature of these sources to balance operational constraints, curtailment strategies, and energy storage. The approach introduces a novel characterization of disturbance scenarios and provides a robust congestion management strategy. Simulation results are compared to a trend-based disturbance estimation baseline. In Mignoni *et al.*, a control strategy for optimizing the scheduling of an energy community with prosumers and unidirectional vehicle-to-grid and vehicle-to-building capabilities is proposed. The strategy considers communication of electric vehicles' parking and recharging time distributions to improve energy allocation. Prosumers and vehicles interact in a rolling horizon control framework to reach an agreement on their operating strategies. The control problem is formulated as a generalized Nash equilibrium problem and solved in a distributed manner using the variational inequality theory. The proposed model predictive control approach is validated through numerical simulations.

F. Sustainability

Sustainable engineering is the process of designing or controlling systems to ensure the sustainable exploitation of resources. Two papers of the special issue fall into this category. Liu *et al.* introduce a stochastic model predictive control strategy for wind energy conversion systems to address the challenges posed by stochastic wind speed uncertainty. The strategy utilizes probabilistic and robust tubes to achieve precise power tracking while ensuring system stability and security. Simulation experiments validate the effectiveness of the proposed controller. In Li *et al.*, a robust short-term dispatch framework is proposed for residential prosumers with solar power generation and battery energy storage. The framework addresses the challenges of nonlinear battery degradation and uncertain generation/load patterns, aiming to achieve minimum-cost operation in a dynamic distribution energy market. The proposed ensemble nonlinear model predictive control-based economic dispatch strategy is validated using real-world prosumer datasets.

G. Smart Infrastructure

The term smart infrastructure includes smart systems that use a data feedback loop to improve decision-making regarding a specific subject. Specifically, the four papers of this category range from water network and sewage treatment to HVAC system and robotic manipulators. In particular, Galuppini *et al.* present a novel multi-node real-time control approach for managing water distribution networks and mitigating leakage issues. The approach involves closed-loop pressure control at multiple nodes using a Kalman filter, auxiliary target calculator, and MPC. Simulations demonstrate satisfactory results, and the approach has low computational complexity and can be tuned using plant data without a hydraulic simulator. In Zhou *et al.*, an enhanced nonlinear model predictive control method for high-performance control of multivariable and non-Gaussian stochastic dynamic systems is presented. It utilizes control error compensation with entropy optimization and state estimation to improve control accuracy. The method combines an extended Kalman filter for estimating system states, a neural network compensator, and kernel density estimation for control error entropy. The proposed approach achieves input-to-state stability and is validated through data experiments in sewage treatment processes. Selvaggio *et al.* present a model predictive non-sliding manipulation control approach for safely transporting objects on a robotic manipulator's tray-like end-effector. The approach ensures non-sliding manipulation and adherence to system constraints by employing a model predictive controller. Extensive simulations and real experiments validate the proposed method. Then, in Lian *et al.*, a novel parallel proximal-point Lagrangian-based solver for nonlinear model predictive control of bilinear systems is proposed. The proposed algorithm converts the non-convex MPC problem into smaller parallelizable sub-problems, enabling efficient real-time computation. The algorithm is validated through simulation and implemented on a microcontroller for DC motor speed control.

H. Healthcare

The healthcare category consists of three papers, all of which focus on MPC-based schemes designed for blood glucose control in patients with diabetes. In Deshpande *et al.*, a closed-loop insulin delivery system using zone model predictive control with an adaptive weighting scheme is proposed. The controller addresses prolonged hyperglycemia by considering changes in insulin sensitivity, profile mismatch, and meal composition. The proposed controller, evaluated through simulations and clinical studies, demonstrates improved glucose control across a range of glucose levels without an increased risk of hypoglycemia. The results highlight the utility and safety of the zone MPC approach. Sun *et al.* propose an event-triggered model predictive control approach for artificial pancreas systems in managing blood glucose concentration for type 1 diabetes. By incorporating a hybrid glucose prediction model and leveraging physiological insights, the approach reduces computational burden and energy consumption while effectively maintaining blood glucose within a safe range. Preclinical simulation studies validate the efficiency and advantages of the proposed approach. Finally, Toffanin *et al.* explore the use of portable devices with improved computational capabilities for artificial pancreas applications. The authors propose a constrained MPC (C-MPC) approach, which is compared to an unconstrained saturated MPC (S-MPC) using a novel simulator. In silico testing on 100 adult patients demonstrates that C-MPC outperforms S-MPC in terms of glucose control. Future developments of patient-tailored C-MPC are suggested to address occurrences of hypoglycemia.

III. Conclusion

This special issue presents a broad survey of state-of-the-art applications of model predictive control and associated developments in optimization and control theory. This outstanding collection of selected contributions affirms the ever-growing potential of this family of optimization-based control techniques across a wide range of application areas.

IV. Acknowledgment

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