Monday, July 19

MS6
Recent Advances in Event-Triggered Control - Part I of II

9:45 AM - 11:45 AM

For Part II, see MS14

Event-triggered controls are controls whose values are only updated when the control system requires attention. This contrasts with standard continuous time or standard sampled-data controls, which do not take the state of the system into account when deciding when to recompute control values. Although emerging computing methods can facilitate recomputing control values, the increasing use of shared wireless (or shared wired) networked systems calls for designing controls that take computation, communication, and energy constraints into account. Event-triggered controls are useful for reducing the use of communication and computational resources, while ensuring desirable control performance such as desired rates of convergence towards equilibria, optimization, and avoidance of undesirable states. However, they require monitoring the performance of control systems, and it can be challenging to ensure their robustness to model uncertainty. Several previous event-triggered control design schemes can be unified from a small-gain perspective. Another approach is the co-design of event-triggered controls and priority assignments, which can resolve contentions in resource-constrained environments. This two-part minisymposium presents an overview of control theory for event-triggered control and recent advances in event-triggered control design for ODEs and PDEs, including applications to marine robotics, parallel computation, safety-critical systems, and traffic management.

Organizer: Fumin Zhang
Georgia Institute of Technology, U.S.

9:45-10:10 Event-Triggered Control and Scheduling Co-Design abstract
Fumin Zhang, Georgia Institute of Technology, U.S.

10:15-10:40 Resource-Aware Control for the Design of Accelerated Optimization Algorithms abstract
Jorge Cortes, University of California, San Diego, U.S.

10:45-11:10 Event-Triggered Safety-Critical Control for Systems with Unknown Dynamics abstract
Christos Cassandras, Boston University, U.S.

11:15-11:40 Event-Triggered Control for Time-Varying Systems using a Positive Systems Approach abstract
Michael Malisoff, Louisiana State University, U.S.; Frederic Mazenc, Inria, France; Zhong-Ping Jiang, Polytechnic Institute of New York University, U.S.; Corina Barbalata, Louisiana State University, U.S.

CT21 Home 2021	Program	Speaker Index	Hotel & Transportation	Registration

Monday, July 19

MS14
Recent Advances in Event-Triggered Control - Part II of II

4:15 PM - 6:15 PM

For Part I, see MS6

Event-triggered controls are controls whose values are only updated when the control system requires attention. This contrasts with standard continuous time or standard sampled-data controls, which do not take the state of the system into account when deciding when to recompute control values. Although emerging computing methods can facilitate recomputing control values, the increasing use of shared wireless (or shared wired) networked systems calls for designing controls that take computation, communication, and energy constraints into account. Event-triggered controls are useful for reducing the use of communication and computational resources, while ensuring desirable control performance such as desired rates of convergence towards equilibria, optimization, and avoidance of undesirable states. However, they require monitoring the performance of control systems, and it can be challenging to ensure their robustness to model uncertainty. Several previous event-triggered control design schemes can be unified from a small-gain perspective. Another approach is the co-design of event-triggered controls and priority assignments, which can resolve contentions in resource-constrained environments. This two-part minisymposium presents an overview of control theory for event-triggered control and recent advances in event-triggered control design for ODEs and PDEs, including applications to marine robotics, parallel computation, safety-critical systems, and traffic management.

Organizer: Michael Malisoff
Louisiana State University, U.S.

4:15-4:40 An Event-Triggered Approach to Speeding Up Parallel Computation abstract
Vijay Gupta and Soumyadip Ghosh, University of Notre Dame, U.S.

4:45-5:10 * On Lyapunov-Krasovskii Methods for Event-Based Control of Retarded Systems with Sampled-Data Measures, Non-Smooth Feedback, and Non-Uniform Sampling abstract
Pierdomenico Pepe, University of L'Aquila, Italy; Alessandro Borri, CNR-IASI, Italy; Mario Di Ferdinando, Universita di L'Aquila, Italy

5:15-5:40 Event-Triggered Control Through the Eyes of Hybrid Small-Gain Theorem abstract
Romain Postoyan, CNRS and University of Lorraine, France; Wei Wang and Dragan Nesic, University of Melbourne, Australia; W.P.M.H. Heemels, Technische Universiteit Eindhoven, The Netherlands

5:45-6:10 Event-Triggered Backstepping for Hyperbolic PDE Sandwiched Between ODEs abstract
Ji Wang and Miroslav Krstic, University of California, San Diego, U.S.

*This presentation is included in the proceedings

CT21 Home 2021	Program	Speaker Index	Hotel & Transportation	Registration

horizon optimal control problems with inequality constraints. Two variants, namely Feasible and Infeasible Interior Point Differential Dynamic Programming (IPDDP) algorithms, are developed using primal-dual interior-point methodology, and their local quadratic convergence properties are characterised. We show that the stationary points of the algorithms are the perturbed KKT points, and thus can be moved arbitrarily close to a locally optimal solution. While general purpose primal-dual interior-point methods are successful in practice, there were no extension of the DDP algorithm accommodating primal-dual interior-point techniques reported so far. Our aim is to fill this gap. The proposed IPDDP framework is a natural extension to DDP. It requires neither modifying the objective function nor identifying active/inactive constraints by a separate procedure. Being free from the burden of active-set methods, it can handle nonlinear state and input inequality constraints without a discernible increase in its computational complexity relative to the unconstrained case. The performance of the proposed algorithms is demonstrated using numerical experiments on three different problems: control-limited inverted pendulum, car-parking, and unicycle motion control and obstacle avoidance. This work is accepted for application in the IEEE Transactions on Control Systems Technology.

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MS5

Tropical Dynamic Programming for Discrete Time Stochastic Optimal Control Problems

In this talk, we consider discrete time stochastic optimal control problems with finite independent noises and Lipschitz continuous costs and dynamics. We present an iterative algorithm which approximates the value function at each time step by both max-plus and min-plus linear combinations of basic functions. If the basic functions added at each iteration are tight and valid, then we have an asymptotic convergence result. We illustrate numerically this convergence result on a toy example with linear dynamics and polyhedral costs.

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MS6

Event-Triggered Safety-Critical Control for Systems with Unknown Dynamics

Solutions to optimal control problems subject to safety-critical constraints have been shown to be obtained through a sequence of Quadratic Programs (QPs) making use of Control Barrier Functions (CBFs). A key challenge in this approach is obtaining accurate system dynamics, which is especially difficult in multi-agent systems where one agent may not have adequate data to estimate other agents dynamics. We propose to define nominal dynamics that are adaptively updated through real-time measurements and a high-order CBF that captures a safety requirement based on the nominal dynamics and error states. This leads to a sequence of QPs whose solution is triggered by specific events. We derive a condition that guarantees the satisfaction of the CBF constraint between events and illustrate how this approach works compared to the conventional time-driven approach for an adaptive cruise control problem.

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MS6

Resource-Aware Control for the Design of Accelerated Optimization Algorithms

This talk takes a dynamical systems and control approach to the design of fast optimization solvers in machine learning. Recent work in the machine learning and optimization communities seeks to shed light on the behavior of accelerated optimization methods via high-resolution differential equations. These differential equations are continuous-time counterparts of discrete-time optimization algorithms and, remarkably, their convergence properties can be characterized using the powerful tools provided by classical Lyapunov stability analysis. An outstanding open question of pivotal importance is how to discretize these continuous flows while maintaining their convergence rates. We provide an answer to this question by employing ideas from resource-aware control. The main idea is to take advantage of the Lyapunov functions employed to characterize the rate of convergence of high-resolution differential equations to design variable-stepsize discretizations that preserve by design the convergence properties of the original dynamics.

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MS6

Event-Triggered Control for Time-Varying Systems using a Positive Systems Approach

We provide new event-triggered control methods, using the notions of interval observers and positive systems. We cover time-varying linear systems, output feedback, and robustness with respect to uncertainty in the dynamics. In each case, our methods ensure global exponential stability of the closed loop system. Our illustrations include a curve tracking system from marine robotics

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MS6

Event-Triggered Control and Scheduling Co-Design

Event-triggered control plays a prominent role in current research in control and optimization, owing to its potential to reduce the computational burden as compared with traditional continuous time or zero-order hold control methods. This talk will provide an overview of recent advances in event-triggered control, including a timing model approach that co-designs controls and priority assignments to resolve contentions in networked systems, and an application to traffic management.

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MS7

Joint Optimization of Sensor Placement and Constant Luenberger Observers Gains

This paper is concerned with a sensor location problems for "optimal" state estimation based on Luenberger observers. The framework is fairly general and applies to both finite and infinite dimensional systems. We consider a general system define on a Hilbert space Z of the form

$$\dot{z}(t) = Az(t) + G\omega(t), \tag{2}$$

with measured outputs

$$y(t) = C(q)z(t) + v(t), \tag{3}$$

where $q \in Q \subseteq \mathbb{R}^d$ is a parameterization of the output operator that determines the location of the sensor and the operators $G : \mathbb{R}^m \to Z$ and $C(q) : Z \longrightarrow \mathbb{R}^p$ are Hilbert-Schmidt. Given the system above a (time independent) Luenberger observer is a linear dynamical system driven by the measured output has the form

$$\dot{z_e}(t) = Az_e(t) + F[y(t) - C(q)z_e(t)] + G\omega(t), \tag{4}$$

where $F \in \mathfrak{B}(\mathbb{R}^m, Z)$. The goal is to find F and q so that the error $e(t) = e(t, F, q) = z_e(t, F, q) - z(t)$ is "as small as possible". We employ different cost functions and formulate several optimization problems to simultaneously optimize sensor location and observer gains. Examples are given to illustrate the ideas and to compare this approach to other methods.

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MS7

Optimal Control of the 2d Evolutionary Navier-Stokes Equations with Measure Valued Controls

In this talk, we consider an optimal control problem for the two- dimensional evolutionary Navier-Stokes system. Looking for sparsity, we take controls as functions of time taking values in a space of Borel measures. The cost functional does not involve directly the control but we assume some constraints on them. We prove the well-posedness of the control problem and derive necessary and sufficient conditions for local optimality of the controls.

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MS7

Control of PDEs with Actuator Guidance Constrained over Time-Varying Reachability Sets

This work focuses on the guidance of mobile actuators employed for the control of PDEs. A practical aspect on the implementation of the actuator guidance considers the mechanical constraints of the mobile platforms carrying the actuators. Terrain platforms cannot behave as point masses without inertia; instead they must satisfy constraints which are adequately represented as path-dependent reachability sets When control algorithm commands a mobile platform to reposition itself in a different spatial location within the spatial domain, this does not occur instantaneously and for the most part the motion is not omnidirectional. This constraint is combined with a computationally feasible and suboptimal control policy with mobile actuators to arrive at a numerically viable control and guidance scheme. The control decision comes from a continuous-discrete control policy whereby the mobile actuator platform is repositioned at discrete times and dwells in a specific position for a certain time interval. Moving to a subsequent spatial location and computing its associated path over a physics-imposed time interval, a set of candidate positions and paths is derived using a path-dependent reachability set. The scheme is demonstrated with a 2D PDE having two sets of collocated actuator-sensor pairs.

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MS7

Analysis and Approximations to the Dirichlet Boundary Control of Stokes Equations

We study Dirichlet boundary control of Stokes flows in 2D polygonal domains. We consider cost functionals with two different boundary control regularization terms: the

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MS13

Ambitropical Convexity: The Geometry of Fixed Points Sets of Shapley Operators

Shapley operators of undiscounted zero-sum two-player games are order-preserving maps that commute with the addition of a constant. The fixed points of these Shapley operators play a key role in the study of games with mean payoff: fixed points that differ, up to an additive constant, determine different optimal stationary strategies. We provide a series of characterizations of fixed point sets of Shapley operators in finite dimension (i.e., for games with a finite state space). Some of these characterizations are of a lattice theoretical nature, whereas some other rely on metric or tropical geometry. More precisely, we show that fixed point sets of Shapley operators are special instances of hyperconvex spaces: they are sup-norm nonexpansive retracts, and also lattices in the induced partial order. Moreover, they retain properties of convex sets, with a notion of "convex hull' defined only up to isomorphism. We finally study the special case of deterministic games with finite action spaces, in which these results become computational. Then, fixed point sets have a structure of polyhedral complex, encompassing both tropical polyhedra and their duals. These polyhedral complexes have a cell decomposition attached to stationary strategies of the players, in which each cell is an alcoved polyhedron of A_n type.

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MS13

Conversion of Nonlinear Second-Order Hamilton-Jacobi PDE Problems into Exact and Approximate Nonlinear First-Order Problems

A class of nonlinear, stochastic staticization control problems (including minimization problems with smooth, convex, coercive payoffs) driven by diffusion dynamics with constant diffusion coefficient is considered. The nonlinearities are addressed through stat duality. The second-order Hamilton-Jacobi partial differential equations (HJ PDE) is converted into a first-order HJ PDE in the dual variable, which contains a correction term. Approximations to the correction term will be indicated. In the subclass of cases where the nonlinearity is only in the zeroth-order term, this may be reduced to a heat equation. More generally, the new form may be converted into an HJ PDE associated to a problem where the controlled nonlinear dynamics interact with a Brownian motion only through a bilinear terminal cost, which has profound numerical implications.

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MS14

An Event-Triggered Approach to Speeding Up Parallel Computation

One of the many uses of parallel computing is to numerically solve partial differential equations. Such numerical simulations involve communication of data among the parallel processing elements. A typical implementation requires such communication at every iteration of the numerical algorithm. As the number of processors increases, the time and energy required for communication turns out to be a major portion of the overall simulation time and energy. Developing strategies to reduce communication without compromising on the quality of the solution are, thus, an important research area. In this paper, we cast the parallel numerical solution as a problem of reaching consensus in a multi-agent system. Consequently, we propose two relaxed communication schemes inspired from consensus in multi-agent systems periodic and event-triggered to reduce communication and, thus, save on simulation time and energy while guaranteeing convergence to the same solution. We model the system as a switched dynamical system and analyze properties such as stability and rate of convergence of the resulting numerical algorithm. The reduction in simulation time and communication energy due to reduced communication is shown through numerical experiments.

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MS14

On Lyapunov-Krasovskii Methods for Event-Based Control of Retarded Systems with Sampled-Data Measures, Non-Smooth Feedback, and Non-Uniform Sampling

In our 2016 SIAM Journal on Control and Optimization paper, we presented an event-based controller for nonlinear retarded systems with these features: i) only sampled-data measures of the Euclidean internal variable are needed and ii) the event function is only evaluated on sampling instants of a partition with dwell time and suitably small diameter, and involves at most a finite number of recent measures. This prior work used a function describing the feedback that needs to be Lipschitz on bounded sets, thus preventing the use of discontinuous feedbacks. This talk shows how discontinuous feedbacks can still be accommodated. We use a Lyapunov-Krasvoskii methodology, and a sampled-data event-based controller with the same features (i)-(ii). The allowed discontinuities are significant, as they include feedbacks which are discontinuous in the current internal variable. With respect to our 2021 L-CSS paper, where even more general discontinuities in the feedback are allowed at the price of only involving commensurate time delays, and of mandatory uniform sampling with suitably constrained sampling period related to delays, here these significant limitations are removed. First order interpolations of sampled-data measures are used for feedback approximation and easy implementation. It is proved that, for suitably small maximal sampling period, semi-global practical sample-and-hold asymptotic stability is guaranteed with arbitrarily small final target ball of the origin.

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MS14

Event-Triggered Control Through the Eyes of Hybrid Small-Gain Theorem

A common approach to design event-triggered controllers is emulation. The idea is to first construct a feedback law in continuous-time, which ensures the desired closed-loop properties. Then, the communication constraints between the plant and the controller are taken into account and a triggering rule is synthesized to generate the transmission instants in such a way that the properties of the continuous-time closed-loop system are preserved, and a strictly positive minimum inter-event time exists, which is essential in practice. Various triggering rules have been proposed in this context in the literature, including relative threshold, fixed threshold, dynamic triggering law to mention a few. We will show in this talk that these seemingly unrelated techniques can all be interpreted in a unified manner. Indeed, it appears that all them guarantee the satisfaction of the conditions of a hybrid small-gain theorem. This unifying perspective provides clear viewpoints on the essential differences and similarities of existing event-triggering policies. Interestingly, for all the considered laws, the small-gain condition vacuously holds in the sense that one of the interconnection gains is zero. We then exploit this fact to modify the original triggering law in such a way that the small-gain condition is no longer trivially satisfied. By doing so, we obtain redesigned strategies, which may reduce the number of transmissions as illustrated by an example.

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MS14

Event-Triggered Backstepping for Hyperbolic PDE Sandwiched Between ODEs

Motivated by vibration control of a mining cable elevator avoiding frequent actions of a massive actuator which is a hydraulic cylinder driving a head sheave, we design an event-triggered output-feedback backstepping boundary controller for coupled hyperbolic PDEs sandwiched by two ODEs, where only the measurement at the PDE actuated boundary is required. The state observer design for the overall sandwich hyperbolic PDE system, and a two-step control design including an output-feedback low-pass-filter-based backstepping boundary stabilization law and a dynamic event-triggered mechanism, are presented. The existence of a minimal dwell-time between two triggering times, and exponential convergence in the event-based closed-loop system are proved. In numerical simulations, the proposed control design is validated in the application of axial vibration control of a mining cable elevator that is 2000 meters deep, and whose dynamics include the hydraulic actuator, mining cable, and cage.

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MS15

Boundary Control for Fluid Mixing: Analysis and Computation

The question of what velocity fields effectively enhance or prevent transport and mixing, or steer a scalar field to a desired distribution, is of great interest and fundamental importance to the fluid mechanics community. In this talk, we mainly discuss the problem of optimal mixing of an inhomogeneous distribution of a scalar field via active control of the flow velocity, governed by the Stokes or the Navier-Stokes equations. Specifically, we consider that the velocity field is steered by a control input which acts tangentially on the boundary of the domain through the Navier slip boundary conditions. This is motivated by mixing within a cavity or vessel by rotating or moving walls. Our main objective is to design a Navier slip boundary control that optimizes mixing at a given final time. Non-dissipative scalars governed by the transport equation will be of our main focus in this talk. A rigorous proof of the existence of an optimal controller and the first-order necessary conditions for optimality will be derived. Computational challenges in solving the optimality conditions will be addressed. Finally, numerical experiments will be presented to demonstrate our ideas and control designs.

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MS15

Indirect Controller Design for Non-Parabolic Par-