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Real-Time Distributed Optimization in Networked Multi-Agent Systems

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14. ABSTRACT

The overarching goal of the project is to establish a systematic on-line use of optimization techniques for real-time applications in networked environments with time-varying stochastic features. Unlike off-line optimization, where one can normally afford computationally intensive
methods, an on-line setting requires fast solutions for time-critical decision making, often in response to unpredictable events. This implies the need to frequently re-solve already hard problems, since conditions in the operating environment are constantly changing. The focus of the
project has been on multi-agent networked systems and the framework developed rests on three conceptual cornerstones: the event-driven paradigm for optimization, data-driven methodologies for optimization algorithms, and scalable on-line solutions for optimal control problems.
The three main objectives are: 1. Develop explicit on-line solutions for dynamic optimization problems in networked systems. 2. Address the question: “When is decentralization possible in networked system optimization?” and develop distributed algorithms for dynamic
optimization in such systems. 3. Address the problem of multiple local minima in network system optimization through efficient ways of escaping such local optima.

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1. ACCOMPLISHMENTS

The overarching goal of the research pursued under grant FA9550-19-1-0158 is to establish a systematic on-line use of optimization techniques for real-time applications in networked environments with time-varying stochastic features. Unlike off-line optimization, where one can normally afford computationally intensive methods, an *on-line* setting requires fast solutions for time-critical decision making, often in response to unpredictable events. This implies the need to frequently re-solve already hard problems, since conditions in the operating environment are constantly changing. The focus of the project has been on multi-agent networked systems, since this is the natural structure characterizing most emerging complex systems, enabled by ubiquitous connectivity and the ability to share enormous amounts of data among the "agents" that define the components of such systems. The term "agent" is used to generically describe the interconnected system components, often mobile devices such as smart-phones, sensors, robots, Uninhabited Autonomous Vehicles (UAVs), or Connected Automated Vehicles (CAVs). The framework developed rests on three conceptual cornerstones: the *event-driven* paradigm for optimization, *data-driven* methodologies for optimization algorithms, and *scalable* on-line solutions for optimal control problems.

1.1. Research Objectives.

Three major research objectives were pursued:

1. Develop explicit on-line solutions for dynamic optimization problems in networked systems. The approach here is to parameterize agent state trajectories in appropriate ways and then optimize them by adjusting them on line. We specifically pursued the use of event-driven algorithms to exploit their scalability, since, as the size of a network increases, the complexity of an event-driven algorithm grows with the number of events associated with each agent and not the (much larger) state dimensionality of the network.

2. Address the question: "When is decentralization possible in networked system optimization?" and develop distributed algorithms for dynamic optimization in such systems. The objective here is to determine whether decentralization is possible without sacrificing the performance of the centralized solution. The goal is to develop explicit distributed algorithms providing the same solutions as centralized ones when feasible; otherwise, the goal is to design feasible distributed algorithms and quantify the loss in performance relative to centralized ones.

3. Address the problem of multiple local minima in network system optimization through efficient ways of escaping such local optima. We have pursued a new method we developed based on the use of *boosting functions* designed to escape local optima by temporarily modifying the objective function gradient and then provably converge, either to a better local optimum or to the original one. The challenge here is twofold: first, select proper boosting functions; second, carry this out in a distributed manner and ensure that the process converges.

1.2. Major Activities and Findings.

1.2.1. The “price of decentralization” in networked system optimization.

We addressed the fundamental question of when decentralization is possible in networked system optimization problems. For a class of such problems that involves persistent monitoring tasks, the objective is to control the movements of cooperating agents in order to minimize an uncertainty metric associated with a finite number of targets. Formulating this as an optimal control problem, we have shown that the optimal solution can be reduced to or approximated by parametric agent trajectory families. The behavior of agents and targets under optimal control can be described by a hybrid system. This enables the use of Infinitesimal Perturbation Analysis (IPA) to obtain an online *centralized* solution through a gradient-based algorithm. We were able to identify conditions under which this centralized solution to the parametric optimization problems can be recovered in a *decentralized* and event-driven manner (see [35]). In the decentralized scheme, each agent optimizes its performance based on local information, except for one type of non-local event requiring communication from a non-neighbor agent, giving rise to a quantifiable “price of decentralization.” Extensive simulation examples demonstrate the effectiveness of this “almost decentralized” optimization algorithm and compare it to its fully decentralized counterpart where the aforementioned non-local event is ignored.

The “price of decentralization” concept was subsequently applied to different classes of networked multi-agent systems. In particular, we considered multi-agent coverage problems with energy-constrained agents, where a charging station is used to replenish an agent’s energy as it becomes depleted while performing the coverage task. We then compared the coverage performance under both centralized and decentralized approaches. A centralized coverage control method was developed to switch agents between an optimal coverage formation and an optimal charging formation (see [33],[43]). We designed a controller for agent trajectories that include dwell times at the optimal coverage locations and charging times at the charging station to maximize a coverage metric over a finite time interval. This controller guarantees that at any time there is at most one agent leaving the team for energy repletion. We also derived a tight bound which allows us to quantify the gap between the coverage performance of the proposed strategy and the unknown globally optimal coverage performance. Comparing the performance difference between the centralized approach and decentralized approach, we have that the centralized approach in general produces better average coverage performance and that the performance gap between the developed algorithm and the globally optimal solution asymptotically vanishes as the number of agents increases.

We also pursued decentralized networked system optimization problems over an infinite horizon where each agent is tasked to gather information so as to minimize the worst-case uncertainty about the internal states of the targets it is visiting. To do this, the agent has to decide its sequence of target-visits and the corresponding dwell-times at each visited target. For a given visiting sequence, we proved that in an optimal dwelling time allocation the peak uncertainty is the same among all targets (see [14],[48]). This allowed us to formulate the optimization of dwelling times as a resource allocation problem and to solve it using a novel efficient algorithm (see [26],[69]).

1.2.2. Escaping local minima in non-convex network system optimization.

We have tackled the problem of multiple local optima arising due to non-convex objective functions very commonly encountered in multi-agent optimization problems. To escape such local optima, we have developed a systematic approach based on the concept of "boosting functions" (see [21],[38]). The underlying idea is to temporarily transform the gradient at a local optimum into a boosted gradient with a non-zero magnitude. Thus, the boosting function approach can be thought of as a process where the local agent objective functions are temporarily altered by defining a set of auxiliary local objective functions whenever an equilibrium (i.e., a local optimum) is reached. Rather than switching the local objective functions, this process is carried out indirectly by systematically transforming the local gradient into a new *boosted gradient*. Consequently, a *boosting function* is formally a transformation of local gradients into appropriate boosted gradients. Clearly, such transformations should always result in nonzero boosted gradients whenever the actual local gradients are zero, so as to enable escaping the local optima. After the next equilibrium is reached following the boosted gradients, we switch back to the original local gradients. Subsequently, the gradient-based algorithm will converge to a new (potentially better) equilibrium point. Compared to methods where gradient components are randomly perturbed to escape local optima, the boosting function approach provides explicitly computed boosted gradients, which ensure both escaping from the local optima and subsequent systematic exploration of the search space. Such desirable qualities can be achieved by designing boosted gradients taking into account structural properties of the objective function as well as information such as the nature of the feasible space where agents can operate.

We were able to develop an explicit *Distributed Boosting Scheme* (DBS) based on a gradient-based optimization algorithm using a novel optimal variable step size mechanism so as to guarantee convergence and shown its applicability to a large class of coverage problems (see [38]). In the DBS, each agent is allowed to asynchronously switch between a "boosting" and a "normal" mode independent of other agents and also without any global communication. To formally establish convergence, we have introduced a novel *optimal variable step size* selection technique, which ensures that the DBS converges. Although the motivation for this approach originated in the multi-agent cooperative coverage control problem, it in fact applies to a broad class of multi-agent systems, beyond coverage or consensus-like problems.

In the course of addressing the problem of multiple local optima in non-convex optimization, we also pursued an alternative way to deal with this issue, by seeking "good" initial points from which to execute gradient-based optimization. For networked multi-agent systems, we developed a computationally efficient off-line greedy technique based on the asymptotic analysis of a network system (see [25],[40]). For the class of persistent monitoring multi-agent systems, a team of agents must visit a set of nodes (targets) interconnected according to a fixed network topology. The aim is to control this team so as to minimize a measure of overall node state uncertainty evaluated over a finite time interval. A class of distributed threshold-based parametric controllers has been used to control agent dwell times at nodes and next-node destinations by enforcing thresholds on the respective node states. Under such a policy, an on-line gradient technique can be used to determine optimal threshold values. However, due to the non-convexity of the problem, this approach often leads to poor local optima highly dependent on the initial thresholds used. Applying the greedy technique we developed, we generated a high-performing set of initial thresholds which were shown through extensive numerical results to be almost immediately (locally) optimal or quickly lead to optimal values.

1.2.3. Event-driven receding horizon dynamic optimization of networked systems

For complex problems with time-varying behaviors, Receding Horizon (RH) optimization methods have proved to be the most effective. In these methods, an optimization problem is solved over a *planning* horizon and its solution executed over a short *action* horizon; the process is then repeated with the planning horizon providing a continuous lookahead capability. In time-driven versions of these schemes, commonly arising in Model Predictive Control (MPC), the action horizon is a fixed time step. However, this can be very inefficient, since it requires repeated solution of a hard optimization problem when in fact this may be unnecessary, especially if the underlying system has an event-driven state transition structure. Thus, we have pursued a distributed *event-driven* receding horizon optimization approach. A critical novel element is that this scheme automatically optimizes its planning horizon length, thus making it *parameter-free*. We have shown that explicit globally optimal solutions can be obtained for every distributed optimization problem encountered at each event where the receding horizon controller is invoked (see [20], [32],[59]).

The same approach was also applied to the problem of estimating the states of a distributed network of nodes (targets) through a team of cooperating agents persistently visiting the nodes so that an overall measure of estimation error covariance evaluated over a finite period is minimized. In this case, each agent solves a sequence of receding horizon optimization problems in an event-driven manner. A novel objective function was introduced so as to optimize the effectiveness of this distributed estimation process. We were able to show that this objective function is unimodal under certain conditions, thus allowing the determination of a unique optimum. Moreover, a machine learning solution was used to improve the computational efficiency of this distributed estimation process by exploiting the history of each agent's trajectory (see [54],[70]).

1.2.4. Dynamic optimization of networked systems with performance and hard constraint guarantees

During the course of the project, we realized the importance of providing guarantees for the satisfaction of hard constraints in the dynamic optimization of networked systems. This is especially true in *safety-critical* systems where safety constraints are critical, such as agents avoiding collisions with external obstacles or other agents, ensuring that agents avoid unsafe regions, or ensuring that they reach target regions subject to temporal specifications. Towards this goal, we adopted the use of Control Barrier Functions (CBFs) and Control Lyapunov Functions (CLFs). This approach was first used in the context of Connected Automated Vehicles (CAVs) where safety requirements are crucial and must be guaranteed (see [6],[12],[18],[22],[26]). This demonstrated the effectiveness of this approach, in which hard constrained dynamic optimization problems are converted into the on-line solution of a sequence of Quadratic Programs (QPs) which are easy to solve. However, the feasibility of these QPs is not always guaranteed, partly due to the time discretization which requires that the decision variables are constant over each time step and partly due to conflicts that may emerge with the satisfaction of constraints on the decision variables themselves.

To address this fundamental feasibility problem, we derived sufficient conditions that guarantee such feasibility at each step of the sequence of QPs being solved (see [50]). We also addressed this problem through the use of real-time data which one can exploit to "learn" how to best maximize the robustness of an optimization problem solution with respect to constraint violations (see [30] [1] ,[74]). Regarding the effect of the time discretization which requires that the decision variables are constant over each time step when solving the sequence of QPs, we have shown that this can be alleviated by using an event-driven approach (see [61],[68]). This approach can also be used to deal with problems where the dynamics of the agents involved are unknown.

We further studied the effect of time-varying constraints and stochasticity in the networked system by introducing *Adaptive CBFS* (aCBFs). Central to aCBFs is the introduction of appropriate time-varying functions to modify the definition of a common CBF. These time-varying functions are treated as high-order CBFs with their own auxiliary dynamics, which are stabilized by CLFs (see [42],[1]).

Temporal specification requirements present additional challenges that conventional CBFs cannot address. We have been able to resolve this challenge by generalizing CBFs to High Order Control Lyapunov-Barrier Functions (HOCLBFs) which we have shown can achieve a given temporal condition (typically expressed through Signal Temporal Logic (STL) formulae) with finite time convergence guarantees (see [55]).

1.3. Dissemination of Results

Result dissemination was accomplished through publications (books, journal articles, refereed conference proceedings) as detailed in Section 4.

In addition, results were disseminated through

- Keynote, plenary and invited lectures and seminars at international conferences, universities, research facilities, and industrial organizations;
- AFOSR PI meetings;
- Workshops and conference invited sessions whose topics were central to the objectives of this project;
- Web sites and online demonstrations of applications based on the results of this project, such as
  https://www.bu.edu/codes/simulations/shiran27/PersistentMonitoring/
  https://www.bu.edu/codes/simulations/shiran27/CoverageBoosting/
  https://www.bu.edu/codes/simulations/shiran27/CoverageGreedy/
  https://www.bu.edu/codes/simulations/shiran27/CoverageFinal/
- Outreach activities organized by the Boston University Center for Information and Systems Engineering (CISE);
- Summer internships offered to high-school students and college undergraduates.

Below is a list of invited presentations made by the PI over the course of this project:

Invited Lecture: A Decentralized Optimal Control Framework for Connected Automated Vehicles. In *2019 American Control Conf. Tutorial Session*. Philadelphia, PA.

Invited Lecture: An Introduction to Cyber-Physical Systems and their Applications.

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[1] Outstanding Student Paper Award at the *59th IEEE Conference on Decision and Control*, 2020

Southeast University, Nanjing, China, 2019.

Invited Lecture: An Introduction to Cyber-Physical Systems and their Applications. Tsinghua University, Beijing, China, 2019.

Invited Lecture: Automating Energy-Efficient Mobility in Smart Cities. In *American Control Conf. Workshop on A Sociotechnical Systems Approach for Energy-Efficient Mobility in Smart Cities*. Philadelphia, PA, 2019.

Invited Lecture: Distributed Multi-Agent Non-Convex Optimization: Seeking Global Optimality Through Boosting Functions. Shanghai Jiao Tong University, Shanghai, China, 2019.

Invited Lecture: How Many Smart Cars Does it Take to Make a Smart Traffic Network? In *2019 IEEE Intelligent Transportation Systems Conf.*, Auckland, NZ.

Invited Lecture: How Many Smart Cars Does it Take to Make a Smart Traffic Network? In *Workshop on Control for Networked Transportation Systems*. Philadelphia, PA, 2019.

Invited Seminar: A Decentralized Optimization Framework for the "Internet of Cars". Chalmers University, Gothenburg, Sweden, 2019.

Invited Seminar: A Decentralized Optimization Framework for the "Internet of Cars". Peking Univerity, Beijing, China, 2019.

Invited Seminar: Systems Engineering: An Interdisciplinary Academic Field for the 21st Century. Tsinghua University, Beijing, China, 2019.

Invited Seminar: The "Internet of Cars". Beijing University of Science and Technology, Beijing, China, 2019.

Invited Seminar: The "Internet of Cars". Shanghai University, Shanghai, China, 2019.

Kwan Chao-Chih Distinguished Lecture: Distributed Multi-Agent Non-Convex Optimization: Seeking Global Optimality Through Boosting Functions. Chinese Academy of Sciences, Beijing, China, 2019.

Plenary Lecture: The Quest for Decentralization and Global Optimality in Multi-Agent Systems. In *2019 IEEE Intl. Conf. on Systems, Man, and Cybernetics*. Bari, Italy, 2019.

Bike Sharing System Inventory Management: Somerville Case Study. In *Boston Area Research Initiative Spring Conference 2019,* Boston, MA.

Congestion Maps: A visual interactive data-driven platform tracking annual traffic conditions in the Eastern Massachusetts area. In *Boston Area Research Initiative Spring Conference 2019*. Boston, MA.

Distinguished Lecture: A Decentralized Optimization Framework for the "Internet of Cars". University of Delaware, Newark, DE, 2020.

Invited Lecture: A Decentralized Optimization Framework for the "Internet of Cars". In *Workshop on Autonomous and Connected Transportation Systems, IEEE Conference on Intelligent Transportation Systems*. Rhodes, Greece [remote], 2020.

Invited Lecture: A Decentralized Optimization Framework for the "Internet of Cars". In *Workshop on Control, Optimization, and Learning Methods for Emerging Mobility Systems, IEEE Conf. on Decision and Control*. Jeju Island, Korea [remote], 2020.

Invited Lecture: How Many Smart Cars Does it Take to Make a Smart Traffic Network? In *Workshop on Traffic Management for Future Mobility, IEEE Conference on Intelligent Transportation Systems*. Rhodes, Greece [remote], 2020.

Invited Lecture: Optimal Lane Change Maneuvers for Safe Swarms of Connected and

Automated Vehicles in Highway Traffic, Chinese Association for Artificial Intelligence. Beijing, China [remote], 2020.

Real-Time Distributed Optimization in Networked Multi-Agent Systems. In *AFOSR PI Meeting, Optimization and Discrete Mathematics*. Arlington, VA [remote], 2020.

Invited Seminar: A Decentralized Optimization Framework for the "Internet of Cars". Tsinghua University, Beijing, China [remote], 2020.

Invited Seminar: Bridging the Gap Between Optimal and Real-Time Safe Control. University of Michigan, Ann Arbor, MI [remote], 2020.

Invited Seminar: Bridging the Gap Between Optimal and Real-Time Safe Control. University of Texas A&M, College Station, TX [remote], 2020.

Keynote Lecture: Bridging the Gap Between Optimal Control and Provably Safe Real-Time Control: Theory and Applications to Autonomous Vehicles. In *2020 IEEE International Conference on Control & Automation*. Sapporo, Japan [remote].

Invited Lecture: Event-Driven Control for Complex Problems in Network Systems. In *Tutorial Series on Discrete Event Systems*. [webinar], 2021.

Invited Lecture: Event-Triggered Safety-Critical Control for Systems with Unknown Dynamics. In *SIAM Conference on Control and its Applications*. [remote], 2021.

Invited Lecture: Optimal and Provably-Safe Decentralized Control of Connected and Automated Vehicles. In *Workshop on Control for Autonomous Cities, 60th IEEE Conf. on Decision and Control*. Austin, TX [remote], 2021.

Invited Lecture: Optimal Assignment Policies for Mobility On-Demand Systems. In *Workshop on Modeling and Control Tools for Sustainable and Connected Mobility in Smart Cities, 2021 IEEE Med. Control Conference [remote]*. Puglia, Italy [remote], 2021.

Invited Lecture: Sustainability in Transportation Systems. In *Interface of Data Sciences and Sustainability Series*. Boston University, Boston, MA, 2021.

Invited Seminar: An Introduction to Cyber-Physical Systems. Southeast University, Nanjing, China [remote], 2021.

Invited Seminar: Bridging the Gap Between Optimal and Real-Time Safe Control. University of California Santa Cruz, CA [remote], 2021.

Keynote Lecture: Bridging the Gap Between Optimal and Real-Time Safe Control: Making Autonomous Vehicles a Reality. In *14th EAI Intl. Conf. on Performance Evaluation Methodologies and Tools*. Guangzhou, China [remote], 2021.

Plenary Talk: Autonomous Vehicles and the "Internet of Cars". In *World Artificial Intelligence Conference*. Shanghai China [remote], 2021.

Invited Lecture: Automating Vehicle Lane Changing and Cooperation Compliance. In *Workshop on Autonomous, Connected and Electrified Mobility Systems: Modeling, Control, and Deployment, 6ist IEEE Conf. on Decision and Control*. Cancun, Mexico, 2022.

Invited Lecture: Autonomous Vehicles and the "Internet of Cars". In *China Automation Congress*. China [remote], 2022.

Invited lecture: Bridging the Gap Between Optimal and Real-Time Safe Control in Autonomous Systems. In *2022 IEEE CSS Workshop on Control for Societal-Scale Challenges*. Stockholm, Sweden, 2022.

Invited Lecture: Event-Driven Control for Complex Problems in Network Systems. In

Colloquium on Discrete Event Systems. Xidian, China [remote], 2022.

Invited Lecture: Learning Methods to Ensure Feasibility in Safety-Critical Cyber-Physical Systems. In *Workshop on Combining Learning and Control in Cyber-Physical Systems,61st IEEE Conference on Decision and Control*. Cancun, Mexico, 2022.

Invited Lecture: Optimal Management of Mobility-on-Demand Systems. In *2022 IEEE International Intelligent Transportation Systems Conference*. Macau, China [remote], 2022.

Invited Seminar: An Introduction to Cyber-Physical Systems. Southeast University, Nanjing, China [remote], 2022.

Invited Seminar: Bridging the Gap Between Optimal and Real-Time Safe Control: Making Autonomous Vehicles a Reality. Beijing Institute of Technology, Beijing, China [remote], 2022.

Invited Seminar: Bridging the Gap Between Optimal and Real-Time Safe Control. Huazhong University of Science and Technology, Wuhan, China [remote], 2022.

Panel organizer: Understanding AI's Potential for Sustainability: Sustainable Mobility. Institute for Sustainable Energy, Boston University [webinar], 2022.

Invited Seminar: Safe Autonomy and Optimal Control with Control Barrier Functions. Raytheon Technologies Research Center, [webinar], 2023.

1.4. Publications Resulted from FA9550-19-1-0158

- **Books Published:**

[1] Xiao, W. Cassandras, C.G., and Belta, C., *Safe Autonomy with Control Barrier Functions: Theory and Applications*, Springer, 2023.

- **Papers Published:**

[2] Zhang, Y., and Cassandras, C.G., "Decentralized Optimal Control of Connected Automated Vehicles at Signal-Free Intersections Including Comfort-Constrained Turns and Safety Guarantees", *Automatica*, Vol. 109, pp. 1-16, https://doi.org/10.1016/j.automatica.2019.108563, 2019.

[3] Chen, R., and Cassandras, C.G., "Stochastic Flow Models with Delays, Blocking and Applications to Multi-Intersection Traffic Light Control", *J. of Discrete Event Dynamic Systems*, https://doi.org/10.1007/s10626-019-00298-6, Vol. 30, 1, pp. 1-29, 2020.

[4] Swaszek, R. M. A., and Cassandras, C.G., "Receding Horizon Control for Station Inventory Management in a Bike Sharing System", *IEEE Trans. on Automation Science and Engineering*, Vol. 17, 1, pp. 407-417, https://ieeexplore.ieee.org/document/8792385, 2020.

[5] Feng, Z., Hu, G., and Cassandras, C.G., "Finite-Time Distributed Convex Optimization for Continuous-Time Multi-Agent Systems with Disturbance

Rejection", *IEEE Trans. on Control of Network Systems*, Vol. 7, 2, pp. 686-698, https://doi.org/10.1109/TCNS.2019.2939642, 2020.

[6] Sun, C., Welikala, S., and Cassandras, C.G., "Optimal Composition of Heterogeneous Multi-Agent Teams for Coverage Problems with Performance Bound Guarantees", *Automatica*, Vol. 117, pp. 1-10, https://doi.org/10.1016/j.automatica.2020.108961, 2020.

[7] Xiao, W., Cassandras, C.G., and Belta, C., "Decentralized Merging Control in Traffic Networks with Noisy Vehicle Dynamics: a Joint Optimal Control and Barrier Function Approach", *Proc. of 22nd IEEE Intl. Conference on Intelligent Transportation Systems*, pp. 3162-3167, 2019.

[8] Swaszek, R., and Cassandras, C.G., "Load Balancing in Mobility-on-Demand Systems: Reallocation Via Parametric Control Using Concurrent Estimation", *Proc. of 22nd IEEE Intl. Conference on Intelligent Transportation Systems*, pp. 2148-2153, 2019.

[9] Houshmand, A., Wollenstein, S., and Cassandras, C.G., "The Penetration Rate Effect of Connected and Automated Vehicles in Mixed Traffic Routing", *Proc. of 22nd IEEE Intl. Conference on Intelligent Transportation Systems*, pp. 1755-1760, 2019.

[10] Salazar, M., Houshmand, A., Cassandras, C.G., and Pavone, M., "Optimal Routing and Energy Management Strategies for Plug-in Hybrid Electric Vehicles", *Proc. of 22nd IEEE Intl. Conference on Intelligent Transportation Systems*, pp. 733-739, 2019.

[11] Chen, R., Cassandras, C.G., and Tahmasbi-Sarvestani, A., "Time and Energy-Optimal Lane Change Maneuvers for Cooperating Connected and Automated Vehicles", *Proc. of 58th IEEE Conference on Decision and Control*, pp. 2220-2225, 2019.

[12] Zhang, Y., and Cassandras, C.G., "Joint Time and Energy-Optimal Control of Connected Automated Vehicles at Signal-Free Intersections with Speed-Dependent Safety Guarantees", *Proc. of 58th IEEE Conference on Decision and Control*, pp. 329-334, 2019.

[13] Xiao, W., and Cassandras, C.G., "Conditions for Improving the Computational Efficiency of Decentralized Optimal Merging Controllers for Connected and Automated Vehicles", *Proc. of 58th IEEE Conference on Decision and Control*, pp. 3158-3163, 2019.

[14] Pinto, S.C., Andersson, S.B., Hendrickx, J.M., and Cassandras, C.G., "Optimal Multi-Agent Persistent Monitoring of the Uncertain State of a Finite Set of Targets", *Proc. of 58th IEEE Conference on Decision and Control*, pp. 4280-4285, 2019.

[15] Meng, X., and Cassandras, C.G., "Trajectory Optimization of Autonomous Agents with Spatio-Temporal Constraints", *IEEE Trans. on Control of Network Systems*, Vol. 7, 3, pp. 1571-1581, 2020. https://doi.org/10.1109/TCNS.2020.2988005

[16] Chen, R., and Cassandras, C.G., "Optimal Assignments in Mobility-on-Demand Systems Using Event-driven Receding Horizon Control", *IEEE Trans. on Intelligent Transportation Systems*, pp. 1-15, 2020. https://doi.org/10.1109/TITS.2020.3030218

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[21] Welikala, S., and Cassandras, C.G., "Distributed Non-convex Optimization of Multi-agent Systems Using Boosting Functions to Escape Local Optima", *Proc. of 2020 American Control Conference*, pp. 2723-2728, 2020. https://doi.org/10.23919/ACC45564.2020.9147395

[22] Pinto, S.C., Andersson, S.B., Hendrickx, J.M., and Cassandras, C.G., "Optimal Periodic Multi-Agent Persistent Monitoring of a Finite Set of Targets with Uncertain States", *Proc. of 2020 American Control Conference*, pp. 5207-5212, 2020.

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2. IMPACTS

Development of the principal discipline(s) of the project:

- In the field of optimization, *non-convexity* of the objective function of interest is a long-standing challenge because of the difficulty in obtaining a global optimum; instead, only local optima can be identified using standard methods (typically, gradient-based algorithms), especially for on-line settings. The use of boosting functions developed in this project has demonstrated the ability to systematically escape such local minima and seek a better one for large classes of networked optimization problems. It is possible that this new optimum is the global one, but that guarantee remains elusive. Nonetheless, boosting function methods have allowed the discovery of better solutions for a large class of networked multi-agent optimization problems, including many long-standing ones such as persistent monitoring and coverage optimization.
- The *event-driven* optimization methods developed in this project provide a critical scalability property, i.e., they easily extend to large networks because their computational complexity increases with the size of the event set required to trigger them rather than the (much larger) state space of a networked system. This is in contrast to *time-driven* methods where an iteration of the optimization algorithm occurs with every time step. In the event-driven approach, an iteration takes place only when a new event occurs, a generally much lower frequency than that of fixed time steps. Moreover, this frees us from the need to select an appropriate time step parameter.
- The use of Control Barrier Functions (CBFs) has enabled the inclusion of *guarantees* for given performance requirement and constraint satisfaction. This is essential in safe-critical systems.

Other disciplines:

The use of *event-driven* methods, in contrast to time-driven methods, is one that applies to a wide range of fields in science and technology that include estimation, communication, and signal processing.

Impact on the development of human resources:

The project has provided exposure of the methods developed and their effect on common technological problems such as autonomous robotic teams and autonomous vehicles in transportation. This has been accomplished through the dissemination of the results (see Section 1.3) to peers, practitioners, and students, some of whom were supported through Research Assistantships funded by this grant. Some high-school and undergraduate students joined the PI's lab and research group as summer interns. A number of webinars and panel sessions were also organized by the PI for the dissemination of results from this project to a wider public consisting of practitioners and policy makers.

Impact on teaching and educational experiences:

New material resulting from this project has been incorporated in courses taught by the PI, and a new course was developed on the topic of "safe autonomous systems". A new book [1] was published and likely to be used by colleagues in institutions worldwide. Web-based resources were developed, including interactive applets (see Section 1.3) involving solutions to well-known networked multi-agent system problems.

A number of doctoral students were supported by this grant and have since graduated and carried the knowledge accumulated from this project to other academic institutions and industrial organizations:

- Shirantha Welikala (PhD obtained, 2021)
- Kaiyuan Xu (PhD expected, 2023)
- James Queeney (PhD expected, 2023)
- Andres Chavez Armijos (PhD expected, 2024)
- Anni Li (PhD expected, 2024)
- Yingqing Chen (PhD expected, 2025)

Impact on physical, institutional, and information resources.

Research results from this project have been used for the development of a laboratory test bed for the control and optimization of multi-agent systems at the BU Robotics Laboratory.