Workshop Abstracts for the
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Multi-Vehicle and Assured Autonomous Control for Aerospace Applications

- Organized by the IEEE CSS Technical Committee on Aerospace Controls -

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Prof. Venanzio Cichella, University of Iowa
Prof. Naira Hovakimyan, University of Illinois, Urbana-Champaign
Prof. Zhihua Qu, University of Central Florida
Dr. Heather Hussain, The Boeing Company, Tukwila, WA
Prof. Gokhan Inalhan, Cranfield University, UK
with additional presentations by:
Prof. Evangelos Theodorou, Georgia Institute of Technology
Prof. Isaac Kaminer, Naval Postgraduate School, Monterey, CA

This one-day workshop will focus on current control system topics that are having an impact in the aerospace industry. The workshop will be presented by leading control systems experts from industry and academia that are involved in some of the most exciting research and development efforts in the field of Aerospace. This workshop is intended for students and professors in search of current applications in need of solutions as well as industry and government professionals interested in potential solutions from academia and adjacent branches of the aerospace industry. This workshop is sponsored and presented by members of the IEEE CSS Technical Committee on Aerospace Controls and their collaborators. The purpose of the technical committee is to help build an international scientific community and promote awareness of outstanding achievements in the field of Aerospace Controls.

In this offering the workshop will present a sample of current topics related to the intelligent control of cooperating groups of unmanned air vehicles (UAV's), spacecraft, drones and miniature projectiles. Our experts will present the theoretical background, rigorous methods and experimental results that are creating an exciting new chapter in field of Aerospace Control. Recent advances in adaptive and nonlinear robust control theory are used to form the basis for safe, resilient and certifiable systems of co-operative platforms. Future directions for research are included in discussion of the roles of artificial intelligence (AI) and augmented and virtual reality (AR/VR), as well as emerging applications in Aerospace Control for adversarially robust cyber resistant systems. The workshop will offer opportunities for questions and answers, and provide an open forum for discussion of applications for current theoretical advances and potential enabling technologies. The proceeds from this workshop will be donated by the organizers and presenters to help fund student awards and participation in CSS technical committee and conference activities.

Agenda

1. **"Towards Trustworthy Autonomy: How AI can help address fundamental learning and adaptation challenges." – Gokhan Inalhan,** Cranfield University, UK

   As Autonomy becomes increasingly ubiquitous in complementing and supplementing humans and human-operated systems, our dependence on them is correspondingly growing. Soon autonomous systems will provide a spectrum of safety-critical, service-critical, and cost-critical functionalities. As such, the major paradigm shift that we currently face is the transition from design-time automated or sand-boxed autonomy; to Artificial Intelligence (AI) enabled self-aware and learning autonomous systems. In that respect, AI enabled autonomy must operate in complex and unpredictable environments, while: (a) accomplishing goals while providing through-life resilience against anomalies, failures and adversaries, and (b) learning and evolving through diverse experiences. In this talk, we will present two key enabling AI technologies and solutions towards addressing these two fundamental challenges with the real-world context. First is physics informed deep learning based digital twin-modelling and its application to wide-body commercial aircraft for high precision fuel modelling and flight planning. The second is reinforcement learning based adaptive flight control system design and trajectory management for unmanned aerial systems. Both of these applications and results demonstrate what AI could bring to real-world modelling and control challenges.

   Professor Gokhan Inalhan (Ph.D. 2004, Stanford University) is BAE Systems Chair, Professor of Autonomous Systems and Artificial Intelligence and Deputy Head of Centre for Autonomous and Cyber-Physical Systems at Cranfield University. He has previously served as Director General of ITU Aerospace Research Centre and ITU Controls and Avionics Laboratories. Gokhan has led and managed numerous grants and industrial projects from FP7, H2020, SESAR, EC Marie-Currie, EPSRC, Boeing, BAE Systems and major Euro-Asian aerospace, defence and aviation companies. He and his research are recipient of awards such as IEEE AESS Exceptional Service Award, Boeing Faculty Fellowship, Council of Higher Education Outstanding Achievement and TUBITAK Innovation Success Stories.

   Professor Inalhan leads the research theme on autonomous systems and artificial intelligence within the School of Aerospace, Transport and Manufacturing at Cranfield University. He and his research group focus on design, modelling, GNC, resilience, and security aspects of autonomy and artificial intelligence for air, defence, transportation and space systems. Current research themes include advanced flight controls and reinforcement learning for autonomous systems, human-autonomy interaction in team concept, urban air and cargo mobility, ATM/UTM, data analytics driven digital twin and surrogate modelling, explainable AI for trustworthy autonomous systems. Gokhan has been serving in Science, Technology and Advisory Boards of various government and commercial entities. His professional service span technical committees (IEEE TCAC, AIAA GNC TC), program and editorial boards in which he has been leading themes including autonomy, intelligent systems and transportation for IEEE CCTA, ICRAT, SESAR SID and AIAA GNC. He is currently the Assoc. Editor-in-Chief of IEEE Transactions on Aerospace and Electronic Systems and Technical Editor of the Autonomous Systems theme. Gokhan is a life-time member and Associate Fellow of AIAA.

2. **"An Optimal Kalman-Consensus Filter for Distributed Implementation over Dynamic Communication Network" –** Matthew D. Howard, Ph.D. Candidate, University of Central Florida and **Zhihua Qu**, Pegasus Professor and Chair, Department of ECE, University of Central Florida, Orlando, FL 32816

   With the rising number of applications for sensor networks comes a need for more accurate cooperative fusion algorithms. In this talk, a distributed and optimal state estimator is presented for implementation through a dynamically switching directed communication network to cooperatively track the state of a dynamic target. In particular, the Kalman-Consensus filter approach is used to incorporate a consensus protocol of neighboring state estimates into the traditional Kalman filter. The main difficulty associated with implementing such an optimal solution on a network of a strongly connected diagraph is its fully coupled covariance matrix, which is highlighted in the talk. In turn, a new distributed algorithm of computing the covariance matrix at every node is developed by taking advantage of the covariance matrix being independent of state estimates. The covariance computation can also be reduced by using the strongly connected diagraph. Should the digraph change over time, a distributed topology estimation algorithm is included to facilitate the implementation of the proposed Kalman-Consensus filters. These advances together render a distributed and optimal solution to the consensus based cooperative Kalman filter design problem, convergence and stability of the proposed algorithms are analyzed and analytically concluded, and their performance is verified through simulation of an illustrative example.

   Prof. Zhihua Qu received his Ph.D. degree in Electrical Engineering at the Georgia Institute of Technology in June 1990. Since then, he has been with the University of Central Florida. He is the SAIC Endowed Professor, Pegasus Professor, and the Chair of Electrical and Computer Engineering Department. Dr. Qu's areas of expertise are nonlinear systems and control, energy and power systems, and robotics. His recent research activities in controls have been cooperative control of heterogeneous dynamical systems with applications to autonomous vehicle systems. Dr. Qu is the author of three books: *Robust Tracking Control of Robot Manipulators* by IEEE Press (1996), *Robust Control of Nonlinear Uncertain Systems by* John Wiley & Sons (1998), and *Cooperative Control of Dynamical Systems with Applications to Autonomous Vehicles* by Springer Verlag (2009). As a co-editor, he contributed the cyber-physical systems security chapters to the book *Smart Grid Control: An Overview and Research Opportunities* by Springer (2018). His research has been supported by governmental agencies (NSF, Army, AFOSR, ONR, NASA, Oak Ridge, DoE) and industry (Lockheed, L3Harris, SAIC, Siemens, and TI). Dr. Qu is a Fellow of IEEE and AAAS and an IEEE Distinguished Lecturer. He is serving or served on Board of Governors of IEEE Control Systems Society, Chair of IEEE CSS TCSG, Past President of ECEDHA, and as Associate Editor for *Automatica*, *IEEE ACCESS*, *IEEE Transactions on Automatic Control*, and *International Journal of Robotics and Automation*.

3. **Aerial Co-robots of the Future: Safety, Intelligence, Certification – Naira Hovakimyan,**

W. Grafton and Lillian B. Wilkins Professor of Mechanical Science and Engineering,
University of Illinois at Urbana-Champaign

This presentation discusses the key challenges of the 21st century and puts the right perspective for development of aerial co-robots of the future by emphasizing safety, intelligence and certification. Each of these three pillars hinge on fundamental theoretical developments for support. Challenges with flight control, cyber-resilience, cooperative path planning, intelligent control, and certification are discussed, and fundamental limitations of feedback loops are revisited for development of safe intelligent control. The fourth industrial revolution challenges new paradigms for certification. Applications in elderly care, scalable e-commerce, and precision agriculture are discussed.

Prof. Naira Hovakimyan received her MS degree in Theoretical Mechanics and Applied Mathematics in 1988 from Yerevan State University in Armenia. She got her Ph.D. in Physics and Mathematics in 1992 from the Institute of Applied Mathematics of Russian Academy of Sciences in Moscow, majoring in optimal control and differential games. Before joining the faculty of UIUC in 2008, she spent time as a research scientist at Stuttgart University in Germany, French Institute for Research in Computer Science and Automation (INRIA) in France, Georgia Institute of Technology, and she was on faculty of Aerospace and Ocean Engineering of Virginia Tech during 2003-2008. She is currently a W. Grafton and Lillian B. Wilkins Professor of Mechanical Science and Engineering at UIUC. In 2015 she was named inaugural director for Intelligent Robotics Lab of Coordinated Science Laboratory at UIUC. She has co-authored two books, six patents and more than 350 refereed publications. She was the recipient of the *SICE International scholarship for the best paper* of a young investigator in the VII ISDG Symposium (Japan, 1996), the 2011 recipient of *AIAA Mechanics and Control of Flight Award*, the 2015 recipient of *SWE Achievement Award*, the 2017 recipient of *IEEE CSS Award for Technical Excellence in Aerospace Controls*, and the 2019 recipient of *AIAA Pendray Aerospace Literature Award*. In 2014 she was awarded the *Humboldt prize* for her lifetime achievements. In 2015 she was awarded the *UIUC Engineering Council Award for Excellence in Advising*. She is Fellow and life member of AIAA, a Fellow of IEEE, and a member of SIAM, AMS, SWE, ASME and ISDG. She is cofounder and chief scientist of IntelinAir. Her work in robotics for elderly care was featured in the New York Times, on Fox TV and CNBC. Her research interests are in control and optimization, autonomous systems, neural networks, game theory and their applications in aerospace, robotics, mechanical, agricultural, electrical, petroleum, biomedical engineering and elderly care.

4. **“Optimal Planning Strategies for Multiple UAV Missions” - Venanzio Cichella,** Assistant Professor, Department of Mechanical Engineering, University of Iowa, Iowa City, IA, and **Naira Hovakimyan,** Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, IL

   Advances in technology and network solutions have enabled operations of multiple unmanned aerial vehicles (UAVs), providing increased reliability and cost effectiveness compared to the use of single large vehicles acting alone. To enable safe deployment of groups of UAVs, these vehicles must be capable of performing missions in a cooperative fashion to achieve common objectives. During these missions, the vehicles must be able to operate safely and execute coordinated tasks in complex, highly uncertain environments while maneuvering in close proximity to each other and to obstacles. This poses multiple challenges inherent to the design, development, and operation of multiple UAVs. Motivated by these ideas, the first part of this talk will introduce and discuss some challenges for the safe operation of multiple UAVs missions in real-world environments. I will focus in particular on the problem of enabling multiple vehicles to perform desired missions in cooperative ways. I will proceed by presenting methodologies aimed at addressing these challenges, with emphasis on our work on real-time optimal motion planning. The presentation will end with current and future research directions, including the design of motion control strategies for UAVs that cooperate with human pilots.

   Prof. Venanzio Cichella received his B.S. and M.S. in Automation Engineering in 2007 and 2011, respectively, from the University of Bologna, Italy. He got his Ph.D. in Mechanical Engineering in 2018 from the University of Illinois at Urbana-Champaign, majoring in planning and control of multiple autonomous systems. He is currently an Assistant Professor at the Mechanical Engineering department at the University of Iowa. His research interests include cooperative control of autonomous systems, collision avoidance, optimal control, machine learning, and human-centered autonomous vehicle design.

5. **“Autonomy in Aerospace at the Intersection of Machine Learning, Control and Physics.” - Dr. Evangelos Theodorou,** Associate Professor, Autonomous Control and Decision Systems Laboratory, School of Aerospace Engineering, Institute of Robotics and Intelligent Machine, Center for Machine Learning, Georgia Institute of Technology

   In this talk, I will present algorithms for safe perceptual decision-making with applications to single and multi-vehicle control and planning. The proposed algorithms are based on concepts drawn from stochastic control, deep learning, large-scale distributed optimization, and parallel computation. I will discuss mechanisms for uncertainty quantification and safety assurance in autonomous and aerospace vehicles and show applications on real and simulated systems.

   Dr. Evangelos Theodorou is an Associate Professor in the School of Aerospace Engineering, at the Georgia Institute of Technology. He is affiliated with the Autonomous Control and Decision Systems Laboratory, the Institute of Robotics and Intelligent Machines, and the Center for Machine Learning at the Georgia Institute of Technology.

6. **“Defense Against Adversarial Swarms with Parameter Uncertainty” - Isaac Kaminer,** Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey CA, **and Venanzio Cichella,** Department of Mechanical Engineering, University of Iowa, Iowa City, IA

Swarms are characterized by large numbers of agents which act individually, yet produce collective, herd-like behaviors. Implementing cooperating swarm strategies for a large-scale swarm is a technical challenge which can be considered to be from the ``insider's perspective.'' It assumes inside control over the swarm's operating algorithms. However, as large-scale `swarm' systems of autonomous systems become achievable---such as those proposed by autonomous driving, UAV package delivery, and military applications---interactions with swarms outside our direct control becomes another challenge. This generates its own ``outsider's perspective'' issues.

In this presentation, we look at the specific challenge of protecting an asset against an adversarial swarm. Autonomous defensive agents are tasked with protected a High Value Unit (HVU) from an incoming swarm attack. The defenders do not fully know the cooperating strategy employed by the adversarial swarm. Nevertheless, the task of the defenders is to maximize the probability of survival of the HVU against an attack by such a swarm. This challenge raises many issues - for instance, how to search for the swarm, how to observe and infer swarm operating algorithms, and how to best defend against the swarm given algorithm unknowns and only limited, indirect control through external means. In this paper we restrict ourselves to the last issue. However, these problems share multiple technical challenges. The preliminary approach we apply in this paper demonstrates some basic methods which we hope will provoke development of more sophisticated tools.

For objectives achieved via external control of the swarm, several features of swarm behavior must be characterized: capturing the dynamic nature of the swarm, tracking the collective risk profile created by a swarm, and engaging with a swarm via dynamic inputs such as autonomous defenders. The many modeling layers create a challenge for generating an effective response to the swarm, as model uncertainty and model error are almost certain. In this paper, we look at several dynamic systems where the network structure is determined by parameters. These parameters set neighborhood relations and interaction rules. Additional parameters establish defender input and swarm risk.

In this presentation we consider generation of optimal defense strategies given uncertainty in parameter values. We demonstrate that small deviations in parameter values can have catastrophic effects on defense trajectories optimized without taking error into account. We then demonstrate the contrasting robustness of applying an uncertain parameter optimal control framework instead of optimizing with nominal values. The robustness against these parameter values suggests that refined parameter knowledge may not be necessary given appropriate computational tools. These computational tools---and the modeling of the high-dimensional swarm itself---are expensive. To assist with this issue, we provide dual conditions for this problem in the form of a Pontryagin minimum principle and prove the consistency of these conditions for the numerical algorithm. These dual conditions can thus be computed from the numerical solution of the computational method and provide a tool for solution verification and parameter sensitivity analysis. The presentation concludes with relevant examples

Prof. Isaac Kaminer received his PhD in Electrical Engineering from University of Michigan in 1992. Before that he spent four years working at Boeing Commercial first as a control engineer in 757/767/747-400 Flight Management Computer Group and then as an engineer in Flight Control Research Group. Since 1992 he has been with the Naval Postgraduate School first at the Aeronautics and Astronautics Department and currently at the Department of Mechanical and Aerospace Engineering where he is a Professor. He has a total of over 30+ years of experience in development and flight testing of guidance, navigation and control algorithms for both manned and unmanned aircraft. His more recent efforts have focused on the development of coordinated control strategies and of vision-based guidance laws UAVs as well as on the optimal defense strategies against a large-scale adversarial swarm. Professor Kaminer has co-authored a book and more than a hundred and fifty refereed journal and conference publications.

7. "The intersection between Machine Learning & GNC" – Heather Hussain, Joseph Gaudio, and James Paduano, The Boeing Company, Tukwila, Washington

As machine learning methods become more prevalent in guidance, navigation, controls, and autonomy (GNC&A), problems of a dynamical nature will increasingly need to be considered. The dynamical nature of these problems may include regressors that are time-varying, necessitating new algorithms in machine learning approaches as well as real-time decision making in the presence of uncertainties using adaptive control approaches. Problems of stability, fast learning with analytical guarantees, and constrained nonlinear systems have to be simultaneously addressed. Some of these problems have to be addressed from a machine learning perspective, while others have to be dealt with using adaptive control approaches. Throughout, analytical guarantees must be considered in order to apply machine learning for decision making in real-time. These theoretical guarantees are necessary to address advanced guidance and control challenges for next generation aerial vehicles. Recently, under the DARPA AlphaDogfight Trials (ADT) program for within-visual-range dogfighting, Aurora Flight Sciences developed competitive AI agents that are robust, trustable and capable. The approach combined reinforcement and machine learning, expert-systems and rule-based methods, and principles from guidance, navigation and control (GNC). Holistically fusing these domains enabled the AI to incorporate domain knowledge and results from traditional disciplines while still leveraging the latest tools from machine/reinforcement learning.

Dr. Heather Hussain received the B.S. degree and M.S. degree in mechanical engineering from the Rochester Institute of Technology, Rochester, NY, USA, in 2012, and the Sc.D. degree in mechanical engineering at the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA in 2017. Her work experience comprises several internships spanning the aerospace and consumer electronics industries– namely, in Product Design at Apple Inc., as a research Scholar at the Munitions Directorate of the Air Force Research Laboratory, and her work in the design and development of verifiable adaptive flight control systems at The Boeing Company. Ms. Hussain's doctoral research at MIT was sponsored by the Boeing Strategic University Initiative under the direction of Dr. Eugene Lavretsky and Dr. Anuradha

Annaswamy. Ms. Hussain joined BR&T's Guidance, Navigation, Control, and Autonomy (GNC&A) group in September 2017. Her research interests lie in adaptive control theory, particularly with applications in aerospace. Ms. Hussain is a member of AIAA and IEEE.

Organizer and Moderator: Dr. Richard A. Hull is a Technical Fellow with Collins Aerospace, leading GNC development efforts in precision guidance systems across several sites. He received a B.S. in Engineering Science and Mechanics from the University of Florida, 1972, and a M.S. and Ph.D. in Electrical Engineering from the University of Central Florida in 1993 and 1996, respectively. He has served as a Guidance and Control System Engineer in the Aerospace Industry for over 50 years, working for Lockheed Martin, Coleman Aerospace, McDonnell Douglas, and Boeing companies. He has formerly served as Vice-Chairman of the Lockheed Martin Corporate Technical Focus Group for Guidance, Navigation and Control. His expertise and experience includes synthesis, simulation and analysis of guidance and control systems for missiles, space launch vehicles, high performance fighter aircraft, and gun launched guided projectiles. He has authored or co-authored over thirty conference and journal articles in the fields of nonlinear or cooperative control. He is a Life Senior Member of Institute of Electrical and Electronics Engineers (IEEE), a senior member of American Institute of Aeronautics and Astronautics (AIAA) and a member of the IEEE Control System Society (CSS). He has served as an Associate Editor of the Conference Editorial Board for the IEEE Control System Society from 1998 to 2008, He is a founding member of the IEEE CSS Technical Committee on Aerospace Control, and currently serves as its chair since. He served as the Local Arrangements Chair for the 50th IEEE Conference on Decision and Control and European Control Conference in Orlando, Florida in December 2011, and helped organize the IEEE TCAC Workshop at the 2012 CDC, the 2017 CCTA the 2019 ACC and 2020 ACC.