Four IEEE Fellows doing research in control are interviewed in this column.

Jorge Cortés is an associate professor at the University of California, San Diego (UCSD). He received a Licenciatura degree in mathematics from Universidad de Zaragoza, Spain, in 1997 and a Ph.D. in engineering mathematics from the Universidad Carlos III de Madrid, Spain, in 2001. He was a postdoctoral research associate at the University of Twente, The Netherlands, and the University of Illinois at Urbana-Champaign before joining the faculty at the University of California, Santa Cruz, in 2004. He moved to UCSD in 2007. He has served or currently serves as an associate editor for many journals, including *IEEE Transactions on Automatic Control, SIAM Journal on Control and Optimization*, and *Systems & Control Letters*. He is the author of more than 150 journal and proceedings papers and of the book *Geometric, Control and Numerical Aspects of Nonholonomic Systems* (Springer-Verlag, 2002) and coauthor of the book *Distributed Control of Robotic Networks* (Princeton University Press, 2009). His research interests are in multiagent systems, distributed optimization, and networked games with applications to robotics, adaptive sampling, and cyberphysical systems.

Ali Jadbabaie is the Alfred Fitler Moore Professor of Network Science at the University of Pennsylvania (Penn), currently on sabbatical as a visiting scientist at the Laboratory for Information and Decision Systems at the Massachusetts Institute of Technology. He received a B.S. with high honors from Sharif University of Technology, Tehran, Iran, in February 1995, an M.S. in electrical and computer engineering from the University of New Mexico in Albuquerque in December 1998, and a Ph.D. in control and dynamical systems from the California Institute of Technology (Caltech) in December 2000. He was a postdoctoral scholar at Caltech and Yale before joining the faculty at Penn in July 2002. At Penn, he has secondary appointments in the Departments of Computer and Information Science and Operations and Information Management in the Wharton School. He is a faculty member of the General Robotics, Automation, Sensing, and Perception (GRASP) laboratory and is the cofounder and director of the Raj and Neera Singh Program in Networked and Social Systems at Penn, which is a new undergraduate interdisciplinary degree program focused on network science and engineering, operations research, and computational social science. He is the inaugural editor-in-chief of *IEEE Transactions on Network Science and Engineering*, a new interdisciplinary IEEE transactions cosponsored by IEEE Computer, Communications, and Circuits and Systems Societies, that launched in 2014. He has served as an associate editor of *IEEE Transactions on Control of Network Systems* and the Informs Journal *Operations Research*. His research interests are in multiagent coordination and control, distributed optimization, network science, network economics, and collective robotics.

William "Mac" M. McEneaney is a professor at UCSD. He received his B.S. and M.S. degrees in mathematics from Rensselaer Polytechnic Institute in 1979 and 1983, respectively, and the M.S. and Ph.D. degrees in applied mathematics from Brown University in 1990 and 1993, respectively. He was an analyst at PAR Technology from 1980 to 1982 and an analyst at the Jet Propulsion Laboratory from 1984 to 1989. Since receiving his Ph.D., he has been at Carnegie Mellon University, North Carolina State University, and, currently, at UCSD. He also acted as a program manager in dynamics and controls at AFOSR during 2008–2009. He has served as an associate editor of several journals including *IEEE Transactions on Automatic Control, Systems & Control Letters*, and *SIAM Journal of Control and Optimization*. He has consulted with many defense contractors, including Lockheed-Martin, Draper Laboratories, United Technologies, Northrop-Grumman, and Tempest Technologies. He has edited two books, *Stochastic Analysis, Control, Optimization and Applications* (with George Yin and Qing Zhang) and *Adversarial Reasoning: Computational Approaches to Reading the Opponent's Mind* (with Alexander Kott) and is the author of *Max-Plus Methods for Nonlinear Control and Estimation* (Birkhäuser, Basel, 2006). He has also authored/coauthored more than 75 journal and proceedings papers. His current research interests are in nonlinear control and game theory and their application to defense, space, and quantum systems.

Anna G. Stefanopoulou is a professor of mechanical engineering and naval architecture and marine engineering at

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the University of Michigan and the director of the Automotive Research Center, which is a U.S. Army Center of Excellence in Modeling and Simulation of Ground Vehicles. She earned her diploma in naval architecture and marine engineering in 1991 from the National Technical University of Athens, Greece, and her Ph.D. in electrical engineering and computer science in 1996 from the University of Michigan. She was a technical specialist at Ford Motor Company in 1996–1997 and an assistant professor at the University of California, Santa Barbara, in 1998–2000. She is the inaugural chair of the ASME Dynamic Systems and Control Division (DSCD) Energy Systems Technical Committee, a member of the SAE Dynamic System Modeling Standards Committee, and a member of a U.S. National Academies Committee on Vehicle Fuel Economy Standards. She has served as an associate editor of *ASME Journal of Dynamic Systems Control and Measurements*, *IEEE Transactions in Control Systems Technology*, and *International Journal of Vehicle Autonomous Systems*. She served as the vice-chair for Industry and Applications for the 2008 American Control Conference and as vice-chair and chair of the Transportation Panel of the ASME DSCD in 1997–1999 and 1999–2002, respectively. She has coauthored a book, *Control of Fuel Cell Power Systems: Principles, Modeling, Analysis, and Feedback Design* (Springer Verlag, London, 2004), ten U.S. patents, five best paper awards, and 200 publications on the estimation and control of internal combustion engines and electrochemical systems such as fuel cells, batteries, and capacitors.

JORGE CORTÉS

Q. How did your education and early career lead to your initial and continuing interest in the control field?

Jorge: That is an interesting question, because I am sort of a latecomer to the control field. I have always had an inclination for mathematics. My father being an engineer probably also helped shape an appreciation for taking an analytical perspective on practical problems. My undergraduate degree was in mathematics. During my senior year, I had the opportunity to do some undergraduate research with Prof. Manuel de León and Prof. David Martín de Diego at the High Council of Scientific Research in Spain, who combined differential geometry and analytical mechanics to study the dynamics of a variety of physical systems. This opened a more applied perspective on the use of mathematics for me, and I ended up doing my Ph.D. in engineering mathematics.

The topic of my Ph.D. thesis was mechanical systems subject to nonholonomic constraints, which are a rich family of systems with a lot of structure that naturally lend themselves to basic control questions such as controllability, motion planning, optimal control, and stabilization. This eventually got me in touch with all the exciting activity on geometric mechanics and control that was taking place at the time at the California Institute of Technology (Caltech), work done either physically there or connected in one way or another to Caltech.

I was hooked by the elegant approach to address such fundamental questions, and I wanted to be part of this activity, so I took advantage of funds for research stays abroad provided by the fellowship I had from the Spanish government to visit Prof. Jim Ostrowski at the GRASP Laboratory at the University of Pennsylvania in 2000 and Prof. Francesco Bullo at the Coordinated Sciences Laboratory at the University of Illinois at Urbana-Champaign (UIUC) in 2001. Both of them were super fun visits that opened my eyes to the control field, and by the time I finished my Ph.D., I was a new convert. I was fortunate enough to get the opportunity to work as a postdoc with Arjan van der Schaft at the University of Twente on gradient realizations of nonlinear control systems. My second postdoc was back in the United States with Francesco at UIUC, right at the time when the field of cooperative control of multiagent systems was taking off, and that put me on the path that I am currently on.

Jorge Cortés with his family in their home's backyard in San Diego, California.

Q. What are some of your research interests?

Jorge: My current research interests revolve around different aspects of networked multiagent systems, focused on algorithm design and analysis motivated by concrete applications. I am interested in distributed optimization problems, where the decisions of individual agents are coupled through their objective functions, the constraints on the network, or both. In such scenarios, agents must collaborate with each other to attain a global optimum. I look for provably correct distributed dynamics that scale gracefully with the number of agents and are robust to disturbances, changes in the network, and such. I am focusing on power networks, although this class of problems finds applications in numerous domains.

A more strategic take on this naturally leads to another area of interest to my group right now, which is networked games. These are games that involve either networked entities as players, forces that operate over networks, or both, and where information is distributed across multiple layers and only partially available to individual players. I find quite fascinating how the interaction between cooperation and competition shapes the behavior in these strategic scenarios. Another area of recent interest is real-time implementation of controllers in distributed setups and, in particular, self- and event-triggered control of cyberphysical systems. The main thrust is to understand to what degree agents can be opportunistic in the transmission and acquisition of information with two goals in mind.

One goal is to preserve guarantees on task completion and robustness of the networked controllers, and the other goal is to make sure that the resulting implementation efficiently uses the sensing, communication, actuator, and computing resources available to the network. I have found the combination of these aspects and the distributed nature of networked multiagent systems to be a fertile area that brings up numerous issues of interest such as autonomy, robustness to uncertainty, and tradeoffs in implementation.

I am also excited about an ongoing NSF-funded collaborative project with the Scripps Institute of Oceanography, where we look at the estimation of ocean flow fields and, in particular, internal waves. These waves are important in oceanography because, as they travel, they are capable of displacing small animals, such as plankton, larvae, and fish. We use a group of buoyancy-controlled drogues that can change their depth in the water column and "be displaced" the same way that small animals are. While underwater, individual drogues do not have access to absolute position information and rely only on inter-drogue measurements to estimate the parameters that define the internal wave. These scenarios have been a source of really interesting control problems. Finally, I maintain ongoing research collaborations on geometric mechanics and control with researchers in Spain going back to the time of my Ph.D.


Jorge during a trip to Sequoia National Park.

Q. What courses do you teach relating to control? Do you have a favorite course? How would you describe your teaching style?

Jorge: Most of the courses related to control that I have taught are at the graduate level: Nonlinear Systems, Nonlinear Control, Hybrid Systems, Cooperative Control of Multiagent Systems, and next year, I hope to be able to teach Game Theory for Engineers. It is really difficult to select a favorite. I love the basics of systems and dynamics, and I always seem to learn or realize a new thing every time I teach Nonlinear Systems or Nonlinear Control. I have developed the other courses I teach at some point in time based on my research interests, and they are indeed close to my heart, as each one is connected with a specific time frame and some paper, set of papers, or book.

The question about the teaching style is interesting. I guess I aim to present things in a way that is as simple and clear as possible (don't we all?). I don't shy away from difficult concepts, but I always attempt (students should tell you if I succeed!) to give the students something they can hang on to get through the abstractions. Another thing I always try to keep in mind is the fact that students are new to the concepts, and I try to take the perspective of how it felt when I was first introduced to them, and what the difficulties in grasping them where, so that I can better frame the exposition. Finally, I try to make the class engaging, with as many questions from students as possible, because it keeps the class's attention up, allows me to calibrate where exactly they are in terms of understanding, and it is more fun. Depending on the course, I like to ask them to do a final project that somehow combines the main take-away messages from the course to make sure they know how to use what they have learned.

Q. What are some of the most promising opportunities you see in the control field?

Jorge: I should start by stating the obvious: my opinion is biased by my own research interests and the areas where I believe that we, as a society, face greater challenges in the future. In terms of areas, I think there are many where control should play an important role. Energy is the first area that comes to mind, with a great variety of control-related problems in applications such as the smart grid, power networks, renewables, and smart buildings. The environment and the sustainable use of the limited resources of the planet is another important area where I believe control could contribute, particularly to things such as water irrigation, precision farming, and ecosystem management. Another area where I also see an increased role for control is transportation systems. The increasing availability of real-time information to all actors involved (consumers, authorities) enables many possibilities, including more efficient choices, better transportation options, and more intelligent

Jorge and his research group, with UCSD's Geisel Library in the background.

infrastructure. The list could go beyond these areas to include social networks, biology, advanced manufacturing, smart medical devices, healthcare, and many others.

A theme that strikes me as common across many of these areas is the observation that, as access to large amounts of information becomes more pervasive, the interconnection and interaction between agents (understood in a broad sense, such as individuals, clusters of individuals, or modes) becomes increasingly significant, unpredictable, and complex. I think systems and control theory can have a significant impact in network science, and specifically in guaranteeing the reliable and safe operation of networked systems across multiple disciplines where autonomy and decisions at the individual level affect the overall system behavior and its performance.

Q. You are the author of two books in the control field. What topics do these books cover?

Jorge: The first book I wrote is *Geometric, Control, and Numerical Aspects of Nonholonomic Systems*, and it is a spin-off of my Ph.D. thesis. The book presents a differential geometric approach to the study of the dynamics of mechanical systems subject to nonholonomic constraints. The term *nonholonomic* refers to the fact that the constraints cannot be expressed in terms only of the configuration variables of the system but instead truly require configuration and velocities. Nonholonomic systems are present in multiple domains, including robotics, locomotion, and multibody dynamics. What motivated me to write the book is the conviction that a better understanding of the geometric structures of mechanical systems helps both analysis and design to solve standing problems and identify new challenges.

The book starts from the derivation of the equations of motion via the classical Lagrange-d'Alembert principle and builds on tools from differential geometry to develop intrinsic, coordinate-free formulations of them. This sets the stage for the study of a variety of classical topics in mechanics; such as symmetry, reduction, and reconstruction of the dynamics, and integrability and control, such as controllability, series expansions, and motion planning. The "geometric emphasis" pays off in many of the results presented in the book, but perhaps this is more apparent in the new class of numerical integration schemes proposed in the manuscript. The book illustrates how the geometric perspective adopted in the design of these integrators explains their provable superior performance with respect to standard numerical methods for nonholonomic systems. These schemes are called *nonholonomic integrators* and have sparked what today is an area of active research in geometric mechanics.

The second book is *Distributed Control of Robotic Networks*, which was cowritten with Prof. Francesco Bullo now at UC, Santa Barbara, and Prof. Sonia Martínez at UCSD. The book is the culmination of a fruitful and prolific collaboration over the years. (I can still remember the fun we had together while writing the book and our endless joint working sessions at coffee shops of Santa Cruz, Santa Barbara, and San Diego.) The book is a self-contained introduction to the cooperative control of networked systems with a distinctive blend of computer

Profile of Jorge Cortés

- *Current position:* associate professor, University of California, San Diego.
- *Visiting and research positions:* University of California, Santa Cruz.
- *Contact information:* University of California, San Diego, Mailstop 0411, 9500 Gilman Drive, La Jolla, California 92093 USA, +1 858 822 7930, cortes@ucsd.edu, http://tintoretto.ucsd.edu/jorge.
- *IEEE Control Systems Society experience highlights:* associate editor, Conference Editorial Board, 2005–2009; chair, Technical Committee on Manufacturing Automation and Robotic Control, 2009–2012; associate editor, *IEEE Transactions on Automatic Control*, 2009–2012; associate editor, *IEEE Control Systems Magazine*, 2012–present.
- *Notable awards:* Young Researcher Prize, Spanish Society of Applied Mathematics, 2006; IEEE Control Systems Magazine Outstanding Paper Award, 2008; SIAM Review SIGEST selection from the *SIAM Journal on Control and Optimization*, 2009; IEEE Control Systems Society Distinguished Lecturer, 2010–present; O. Hugo Schuck Best Paper Award, American Automatic Control Council, 2012; IEEE Fellow, 2014.

science, control theory, and robotics. The first two chapters cover fairly general concepts and techniques currently used for distributed and multiagent systems, such as graph theory, distributed algorithms, matrix theory, and geometric notions. The book also puts forth a model for robotic networks, including complexity measures, to help rigorously formalize coordination algorithms running on them. The remaining chapters present cooperative strategies to achieve a variety of coordination tasks, such as connectivity maintenance, rendezvous, deployment, and estimation. The book is freely available online—from its inception, we were sure about this choice to maximize its accessibility and impact —and based on the feedback we have received from the community, I am very glad that we made this choice.

I would really like to write a third book, on discontinuous dynamics and nonsmooth systems. I have not found the time yet but I hope I will; a few years ago I wrote a tutorial on the topic for *IEEE Control Systems Magazine* that many people have found useful, so that would be for sure my starting point.

Q. What are some of your interests and activities outside of your professional career?

Jorge: I like reading modern literature; watching good-quality TV series on Netflix; playing and watching soccer; running, hiking, exercising in general; and swimming in the hot days of summer. Over the last few years, I have not practiced these activities as much as I used to because of the arrival of my son (four years old) and daughter (one year old). My wife and I love spending time with them, and I would say they are our main activity, professional or otherwise!

Q. Thank you for your comments.

Jorge: Thank you for the invitation and the opportunity to reach the *IEEE Control Systems Magazine* readership.

ALI JADBABAIE

Q. How did your education and early career lead to your initial and continuing interest in the control field?

Ali Jadbabaie.

Ali: My choice of control systems as a major happened somewhat through serendipity. I entered college in 1990. At the time, electrical engineering was the hottest engineering discipline in Iran and was divided into four branches: electronics, communications, control, and power systems. The top 20–30 students (out of roughly 250,000) in the National Entrance mostly selected electronics at Sharif University. Following the herd mentality, I did the same. For my second choice, I chose control systems because I had heard it was more "math based" and I liked math. I ranked 45 in the exam, so I did not make it to my first choice.

Q. What are some of your research interests?

Ali: My interests are broadly on the interplay of network dynamics and optimization, in a variety of contexts. Early on in my career, I worked on coordination and control of multirobot formations. Later I became interested in networks, learning, opinion dynamics, and applications to social and economic systems.

Q. What courses do you teach relating to control?

Ali: I have been mostly teaching optimization courses over the last six years. In the fall semester, I teach a course on linear programming, duality, integer programming, and network flows. In the spring, I teach a course on convex optimization theory, applications, and algorithms. I have also taught special topics courses on networked dynamic systems.

Q. What are some of the most promising opportunities you see in the control field?

Ali: I think ideas from decision theory and control, interpreted broadly, have an important role to play in many applications ranging from robotics to data science, network science, and economics, as well as synthetic and

Ali in his office.

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