Profile of Kirsten A. Morris

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- *IEEE Control Systems Society experience highlights:* vice-president for Technical Activities (2015–2016); vice-president for Membership Activities (2013–2014); Board of Governors (2010–2012): associate editor, *IEEE Transactions on Automatic Control* (2008–2013), associate editor, Conference Editorial Board (2000–2007).

I tried to keep a theme throughout of the tradeoff between performance and maintaining stability despite system uncertainty.

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

Kirsten: For a long time my non-work time focused on my two sons, who are now at university. One is studying computer science, and the other is in mechatronics. My sons come from a line of engineers. Not only am I an engineer, both uncles, my grandfather, and my great-grandfather were engineers, so maybe it is in our genes. I play the oboe and am a member of a local wind orchestra, which is very enjoyable and a good way to make friends. I also enjoy listening to music, and, now that my sons are not at home, I go to more concerts. I also run regularly; my favorite route is through the woods near my house.

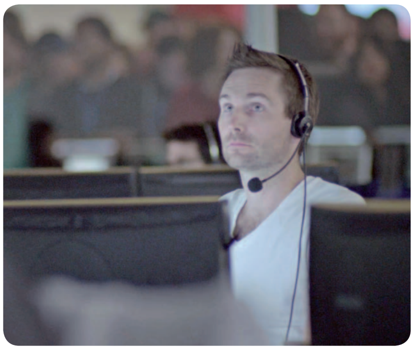
Q. Thank you for your comments.

Kirsten: Thank you for the opportunity to share some of my experiences.

LARS BLACKMORE

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

Lars: Control first fascinated me because it's about how we can use mathematics to influence, and interact with, the physical world. This interface was always interesting to me because we have to have both theoretical understanding and physical intuition, whereas other fields require only one or the other. I've always been interested in high-performance vehicles, and I was lucky enough to do my master's thesis under Prof. Keith Glover, in collaboration with the McLaren Formula One racing team. I became interested in theoretical results that could show demonstrable benefits to how you can drive or fly a vehicle. Although Formula One is an extremely exciting environment, ultimately I decided that I wanted to solve problems that are im-



Lars Blackmore in mission control for the first successful Falcon 9 landing.

posed by physics, rather than a human-made set of rules. This drew me to space travel and, in particular, the idea of developing autonomous vehicles to land on and explore other planets. This took me from the United Kingdom to the United States and a Ph.D. at MIT under Prof. Brian Williams.

Around that time, there were both spectacular successes and disappointing failures of planetary landers, which convinced me that landing was a very challenging but exciting field. Unfortunately, the same period saw the International Traffic in Arms Regulations law introduced, which made working in space research as a foreign national extremely challenging. Thanks to some heroic efforts from my professors and employers, I was nonetheless able to join the NASA Jet Propulsion Laboratory (JPL), where I did research on Mars precision landing and developed control algorithms for the currently orbiting Soil Moisture Active Passive climate-change mission.

Q. What is the goal of the SpaceX rocket landing project?

Lars: Launching payloads into space is still extraordinarily expensive, despite decades of research. One of the reasons for this is that rockets are expendable—after delivering the payload, they simply fall away and burn up in the atmosphere. Since propellant makes up less than 0.5% of the cost of a launch, if we can make rockets that can land, refuel, and refly like an airplane, we think we will

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significantly reduce the cost of getting to space. At SpaceX, we've been working on landing the first stage of our Falcon 9 rocket. The first stage is the largest and most expensive part of the rocket—and the most practical to reenter and land. We've now had three successful landings on our floating ocean platform and one successful landing on land at Cape Canaveral. The plan is to refly one of these landed stages by the end of the year.

Q. What are the control challenges with landing the rocket?

Lars: Entry and landing for the Falcon 9 first stage is an exceptionally interesting guidance and control problem. The rocket is about 16 stories tall, enters the atmosphere at over six times the speed of sound, and must land accurately to within ten meters or better to stay on the landing platform. For comparison, the most accurate Mars landings so far have been able to guarantee landing within ten kilometers of their target, so precision landing is essential. The vehicle itself is quite unique in that it can't rely on the control authority that wings give an airplane, nor can it rely on the high ballistic coefficient and high speed that a ballistic missile uses to ensure precision.

The landing burn is particularly interesting, and many familiar control challenges arise: nonminimum-phase zeros; slosh and bending modes; nonlinear aerodynamics that cause control reversals at high speeds; and large, stochastic disturbances (caused by winds). For guidance, since the landing burn is our last opportunity to bring the rocket to the target, we need to be able to compute a trajectory onboard and replan during the burn, if required. The problem of finding an optimal trajectory that takes into account the six-degrees-of-freedom dynamics of the vehicle—including aerodynamics and winds, with guarantees on finding a solution, if one exists—is a very interesting one.

Q. What are some of your research interests?

Lars in front of the (actual size) Falcon 9 landing leg.

Lars: In the past few years I have been focused on precision landing—in particular, guidance, navigation, and control for the landing burn. This is an application where we need to find optimal trajectories in highly time- and computation-constrained situation. If we fail to find a feasible solution in time, we will crash a (maybe billion-dollar) spacecraft into the ground. If we fail to find the optimal solution, we may use up our available propellant, with the same result. A general solution to such problems has existed in one dimensional since the 1960s, but not in three dimensional (3-D).

Prior to SpaceX, I worked with Behcet Acikmese at JPL, who had shown how we can use "lossless convexification" to turn the nonconvex 3-D problem into a convex one, solve it using standard interior-point methods, and guarantee rigorously that the solution of the convex problem is the global optimum to the original nonconvex problem. Together, we developed a collection of theoretical results that enabled a set of algorithms for precision landing on Mars, now known as G-FOLD. Since then, I've been working on Earth landing for Falcon 9. This is a very different problem; Earth's atmosphere is 100 times as dense as that of Mars, so aerodynamic forces become your primary concern, rather than a disturbance to be neglected. Still, we've been able to use different theoretical results and high-speed convex optimization (thanks to Stephen Boyd and Jacob Mattingley's CVXGEN software) to generate our powered precision-landing trajectories in hundreds of milliseconds on the rocket's onboard computer.

I'm also interested in chance-constrained guidance and hybrid discrete-continuous systems. Chance-constrained guidance is the problem of planning a trajectory under stochastic uncertainty, such that the probability of failure (for example, collision with an obstacle) is below a certain user-specified bound. By adjusting that bound, the user can trade off risk and performance. I have published several papers on algorithms that solve this problem either approximately or conservatively, where the interesting part is how to avoid introducing too much approximation error or too much conservatism. For hybrid discrete-continuous systems, I'm interested in state estimation and, in particular, how we can choose control inputs that improve the accuracy of our state estimate.

Q. What is your experience of guidance and control at SpaceX?

Lars: SpaceX is an excellent environment for algorithm development. While the control problems are highly challenging, we have the unique situation with first-stage landings, where the rocket will definitely not survive if we don't even attempt to land it. As a result, we can tolerate more risk and more experimentation than typical space missions, where failure is not an option. Even on the flights where we did not succeed in landing, we learned a lot from the telemetry and used that to improve our algorithms and operations. In many cases, we changed the rocket hardware as a result of these early tests, for example, adding fins.

In addition, my team tries to find the best solution starting from a blank sheet of paper, rather than being constrained to using algorithms

Profile of Lars Blackmore

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that have flown in previous missions. This means a new algorithm can go from concept to flight testing in months rather than years or decades. Members of the guidance, navigation, and control team also get to be part of mission control for launch, which is very exciting. Overall, SpaceX is a great place for people interested in developing and flying new guidance and control algorithms.

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

Lars: I believe there are many opportunities where the performance, reliability, and autonomy of space vehicles could be improved through recent advances in the control field. One example is onboard convex optimization. Convex optimization is, of course, ubiquitous in the control literature but has not yet been widely used in autonomous space vehicles, for three reasons. First, we need theoretical results, such as lossless convexification, that can pose space-relevant problems in a convex form. Second, even if we can use convex optimization, flight computer computational resources may be too limited. This is particularly true in the case of Mars landers, where radiation shielding is required and computing speeds are unlikely to improve in the foreseeable future. Recent advances in high-speed convex optimization can, however, overcome these resource constraints. Finally, the space industry traditionally associates optimization with offline trajectory generation, which is a highly nonconvex problem requiring a human in the loop to pick a good initial guess and coax the solution towards the global optimum. Convex optimization, by contrast, can guarantee finding the global optimum in a predetermined number of steps and so is appropriate for onboard, mission-critical applications. I believe that overcoming this perception gap and providing theoretical and experimental evidence that convergence is guaranteed will open up many opportunities for the application of convex optimization onboard.

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

Lars: I play in a soccer league, scuba dive, and ski. I love traveling. Aside from that, Los Angeles has a great music scene, and I try to get out and see as many shows as I can.

Q. Thank you for your comments.

Lars: Thank you, it has been my pleasure!

MRDJAN JANKOVIC

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

Mrdjan: During my undergraduate electrical engineering studies in Belgrade (then Yugoslavia), I selected the automatic control subspecialty not knowing much about it or about the other options. After graduation and before coming to the United States, I worked for a year in a university-research type position developing microcontrollers for induction motor control. After that, somehow, at each fork in the road of my career I selected the control field option. My guess is that a blend of mathematical rigor and practical applicability is what attracted me to and kept me in the field.

Q. What are some of your research interests?

Mrdjan: As a part of my job, I have worked on powertrain control. A few prominent projects include air-path control for Ford EcoBoost (gasoline turbocharged direct-injection) engines, air-fuel ratio and after-treatment controls, and a high-degree-of-freedom scheduler for optimization variables such as variable valve timing and exhaust-gas recirculation rate. A powertrain control system is used and reused with very little change between vehicle platforms. Hence, the control

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