In this issue of IEEE Control Systems Magazine (CSM) we speak with George Schmidt, who is a lecturer in aeronautics and astronautics at MIT and an industry consultant in guidance, navigation, and control. George has worked on control system design for missiles, aircraft, and manned spacecraft, Kalman filtering applications, and integration techniques for high-resolution synthetic aperture radars, satellite navigation systems, and inertial sensors. He is an AIAA Fellow and an IEEE Life Fellow, and he has been editor-in-chief of the AIAA Journal of Guidance, Control, and Dynamics since 1996.

We also speak with Wolfgang Marquardt of the RWTH University Aachen, Germany. Wolfgang is an IFAC fellow, and he is editor-in-chief of the Journal of Process Control. His expertise is in chemical process systems, process operations and control, model-based experimental analysis of chemical process systems, and numerical methods for dynamical simulation and optimization.

**GEORGE SCHMIDT**

Q. Can you briefly describe your background in aerospace engineering.

George: I grew up in New Jersey near Newark and was always fascinated by the airplanes taking off and landing at the airport. When I was a sophomore in high school, Sputnik 1 was launched, and that inspired me to become a member of the aerospace profession. In 1960 I went to MIT to study aeronautics and astronautics, eventually receiving the S.B. and S.M. degrees in 1965 and the Sc.D. in instrumentation in 1971. But my professional career really started in 1961 when I started working at the Instrumentation Laboratory (the I-Lab), part of the Department of Aeronautics and Astronautics. The I-Lab was led by the head of the department, Charles Stark Draper, who has been called the father of inertial guidance. The I-Lab seemed like a good place to work part time as it was only a block away from the MIT classrooms, and guidance and navigation based on inertial navigation sounded like magic. So I went to see Doc Draper about getting a job. “Sure” he said. “Go see Eleanor in Personnel.” So began my career. And in that year, 1961, the I-Lab was awarded the first NASA contract in the United States to start work on the Apollo Program to develop the guidance, navigation, and control (GNC) system for the spacecraft. I was very lucky to be in the right place at the right time. The I-Lab was divested by MIT in 1973 and renamed the Charles Stark Draper Laboratory. In 2007, I retired after 46 years of continuous service.

Q. What kinds of projects were you involved in at Draper Labs?

George: The 1960s at the I-Lab were fantastic. In 1965, I completed my S.M. thesis research on the application of Kalman filtering for pre-launch alignment and calibration of the Apollo inertial measurement unit. I then became a member of the technical staff and actually implemented my research into the onboard Apollo guidance computer. In 1966 the algorithms began to be routinely used in the spacecraft. A 13-state filter was employed operating in a slow onboard computer. This was the first application of Kalman filtering to a production inertial system. Best of all, I actually got to train many of the Apollo astronauts when they visited Cambridge, and I worked in the spacecraft control room at Cape Kennedy for every flight through Apollo 13.

When I finished my Sc.D. thesis in 1971, I decided I needed to learn more about frequency-domain problems so I transferred from NASA programs to work on Air Force programs. I was asked to work on the motion compensation needed for implementation of synthetic aperture radars (SAR) in high-speed platforms. Well, it turned out to be another time-domain problem with filtering involved, so I hadn’t escaped at all! But it was tremendously interesting and eventually involved B-52 flight testing. Nowadays, SAR is commonly implemented in strategic bombers and tactical aircraft.

Late in the 1970s, I got a chance to work on defining the avionics...
requirements to launch TERCOM-equipped cruise missiles from wide-body aircraft. The program never progressed, but I learned about strategic aircraft and strategic cruise missiles. I proposed a study to the Air Force that would define the avionics requirements for future strategic aircraft and strategic cruise missiles that would be significantly less dependent on TERCOM. I am pleased to say that today many of the key study recommendations were implemented in the unique B-2 navigation system and also in the stealthy Advanced Cruise Missile (ACM). Four hundred sixty-one ACMs were produced and are now in the process of being retired from service. Fortunately, these nuclear-equipped, stealthy missiles were never used, but they were part of the strong deterrent we presented to the Soviet Union.

Throughout the 1970s and into the 1990s, global positioning satellite (GPS) development and applications were proceeding at a furious pace. The Defense Department was beginning to understand that the GPS signal was fragile in the sense that a determined opponent could jam the received signal. I was fortunate to serve on several panels, including the Defense Science Board Task Force on GPS, that looked at ways to preserve our ability to use GPS in a hostile environment while denying an enemy’s ability to use GPS. As a result of that study, a large national program, NAVWAR, was started that developed many improvements to address future military needs. One of those improvements was to develop advanced inertial system/GPS integration techniques to increase the antijam capability of the system. Since inertial systems cannot be jammed, they offer the ability to provide accurate navigation throughout a period of GPS jamming.

In 1998 I became the education director of Draper Laboratory. As part of the 1973 MIT divestiture of the I-Lab, Draper Laboratory continued to have MIT graduate students do their thesis research at the laboratory. From 1998 through 2007 when I retired, each year we had about 60 graduate students from MIT doing research. In addition, I was directing a US$2 million per year university research program with typically 18 projects a year at MIT and universities throughout the country.

When I retired from Draper Laboratory, I felt I accomplished my goal to be a successful aerospace engineer, that I contributed to nationally important projects, and that I also contributed to developing the next generation of technical leaders of our nation. Now I am concentrating on teaching, consulting, and my AIAA and IEEE professional activities.

Q. You’re active in the NATO Research and Technology Organization, which used to be called AGARD. Can you describe the kinds of control-related technology that this group is involved in.

George: The NATO Advisory Group for Aerospace Research and Development (AGARD) was formed by von Kármán in 1952. The NATO Defense Research Group (DRG) was formed later, and about ten years ago they were combined as the NATO RTO. RTO promotes and conducts cooperative scientific research and exchange of technical information among 28 NATO nations and 38 NATO partners. The effort is managed by an executive agency, RTA, which facilitates collaboration by organizing a wide range of studies, workshops, symposia, lecture series, and other forums in which researchers can meet and exchange knowledge. Actual research activities are supported by the member nations themselves, not by RTO, so research contracts are not issued by RTO. Six RTO panels are actively involved in conducting these cooperative activities. A complete list of activities and publications is given at www.rto.nato.int. I believe control is an enabling technology/GPS integration techniques to increase the antijam capability of the system. Since inertial systems cannot be jammed, they offer the ability to provide accurate navigation throughout a period of GPS jamming.

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Q. In 2005 you were awarded the NATO Research and Technology Organization’s highest technical award, the von Kármán Medal. What contributions led to that specific recognition?

George: Beginning in 1968, I started to contribute to the NATO research organization technical programs as a paper presenter at conferences, as a research study group member, as a conference organizer, and as a lecture series director. I believe I hold the record for organizing the most NATO lecture series focused on specific topics of NATO interest. After the fall of the Iron Curtain, I organized the first lecture series in Russia. I also used my NATO connections to find international advisors for the Journal of Guidance, Control, and Dynamics. At the time of the award in 2005, the contributions to NATO international programs had spanned 37 years, and
technology that can be found in virtually all of the RTO activities listed on the Web site, which includes the complete scope of defense technologies.

Q. What do you view as some of the key current challenges in aerospace engineering related to guidance and control?

George: I believe we are on the path to achieving worldwide 1-m combined INS/GPS navigation accuracy at low cost with robustness to interference. INS systems will be based on MEMS technology, so they will be small, lightweight, and use little power. Improvements in the accuracy of GPS are already nearing that accuracy goal, and so is the INS/GPS antijam capability. However, the greatest challenge is improving MEMS gyro and accelerometers by two orders of magnitude in performance. If that can be achieved, we will have small size, low cost, and high performance. The uses of INS/GPS will proliferate. Individuals, including civilians and soldiers, will have personal navigators, guided artillery shells will have superb accuracy, and robots will be able to accomplish un-thought-of missions. Other applications will surely include spacecraft, aircraft, missiles, commercial vehicles, and consumer items. The second challenge will be in preparing maps that have better than 1-m accuracy in which the INS/GPS will navigate. There is a third challenge, which is to harness the increasing power of onboard computers. Implementing algorithms such as nonlinear filters is becoming possible now even though they were dismissed as impractical a few decades ago.

Q. The AIAA Journal of Guidance, Control, and Dynamics (JGCD) is one of the premiere control-related journals in the aerospace field. Congratulations on your “guidance” of that publication since 1996. Modestly speaking, of course, how have you managed to bring the publication to its current state of distinction? Also, what advice do you have for authors who wish to submit articles for publication?

George: Thank you for the kind words. The JGCD was started in 1978 by Donald Fraser, and under his leadership for 14 years it rose to a high status. Terry Alfriend continued that stewardship until 1996. When I started, the JGCD was in excellent shape and well beyond any startup transient effect.

More than any individual, the 23 associate editors (AEs) control the quality of the journal, and that is what I try to stress when I recruit them. Selecting the AEs is my most important job. I regularly update my list of outstanding reviewers for potential AEs. The JGCD has been lucky to have three AEs serve at least as long as I have served. The retirement rate of AEs, who serve three-year terms, is very low, typically three per year. That allows a very real continuity in review quality in our technical areas. I try to balance the number of AEs equally among academia, industry, and government laboratories. The JGCD is supposed to be an applications-oriented journal so it is important to balance the different AE backgrounds.

As for author advice:
1) Read all the way through the submission requirements on the Web and then follow them exactly.
2) Clearly identify your contribution and its relationship to prior work as documented by references preferably chosen from peer-reviewed publications.
3) Make sure all sentences are grammatically correct and make sense technically! Non-English speaking authors should note that they only get three chances to submit in grammatically correct English. Reviewers will not review papers when they have to correct the grammar.
4) If your paper is a bunch of equations followed by some trivial, simulated aerospace example, don’t submit. Revise it to show you can solve some practical aerospace problem.

Q. You were education director at Draper Labs. What trends do you see in control-related education?

George: I still teach a graduate course at MIT, and one positive trend that is obvious to me is that there is now greater collaboration between faculty, even in different departments. For example, control, communications, software, and other faculty are conducting interesting systems-level research involving graduate students in transportation systems, satellite constellation design, as well as in bio-inspired navigation. The theses produced by these students are truly amazing. My only complaint is that it seems as if mathematics is a foreign language to some students. I don’t know what the cause is, but I am convinced that many students cannot do the rigorous analytical work required in graduate school. Can it be the over-dependence on computers and canned analysis programs? But my major concern is the decreasing financial support by the government and industry that is leading to a future disaster in the number and quality of engineers we graduate.

Q. What are your interests outside of professional activities?

George: I have two married sons and three grandchildren under two years old. Fortunately, I see and provide day care to two of them often. I have a house in New Hampshire on a lake and enjoy boating in the summer and skiing in the winter. I also like to travel, preferably internationally. And I have the best long-term companion, Judy, whom I could imagine or dream about.

Q. Thank you for speaking with CSM!

George: You’re most welcome.
WOLFGANG MARQUARDT

Q. What are some of your research projects in process control?

Wolfgang: The focus of our research in process control is on the development of methodologies and algorithms for dynamic real-time optimization (D-RTO) of process and energy systems, such as a chemical plant or a power plant, which are typically modeled by a large number of nonlinear differential-algebraic equations. D-RTO is a variant of nonlinear model-predictive control with an economical objective. Rather than tracking a constant or time-varying setpoint and attenuating fast disturbances in the traditional setting in systems and control, our goal is to operate the plant at all times in an economically optimal manner. In particular, the “control” objective is the maximization of profit during a finite-time horizon campaign despite the time-varying nature of the environment the plant is operating in. The disturbances acting on the plant include fast, typically random disturbances with zero mean as well as slow disturbances with nonvanishing trends on different time scales. These can either be endogenous and a consequence of operator interaction, a gradual deterioration of the performance of the equipment, exogenous resulting from ambient pressure and temperature fluctuations, changes in the processed raw materials, or in the desired product qualities and quantities. Consequently, setpoint generation as well as setpoint tracking are intertwined problems that are solved either by an integrated approach as in nonlinear model-predictive control or by a hierarchical decomposition approach accounting for the different time scales of real-time (reactive) production planning and scheduling, economical optimization of typically time-varying setpoints, and of disturbance rejection and stabilization. The decision variables are not only the control variable setpoint trajectories but are also integer variables encoding some operational strategy or the startup or shutdown of a unit in a plant.

In recent years, we have developed powerful optimal control algorithms that aim at a fully adaptive solution strategy of the dynamic optimization problems to achieve robustness as well as computational efficiency in a fully nonlinear setting. Furthermore, we always emphasize a late discretization approach to fully exploit the power of numerical algorithms rather than looking at the discrete-time problem. More recently, we have worked on neighboring extremal control to reduce the computational effort and to develop consistent decomposition strategies in a hierarchical approach. Most recently, we’ve been interested in decentralization aspects to deal with functional decomposition of large plants either to reduce complexity of the optimization scheme or to deal with different time-scale processes. Modeling and model tuning including integrated parameter and state estimation to fight the inherent process and model uncertainty becomes the true challenge if these control systems are applied to a real industrial process.

Q. What do you view as the most challenging problems currently facing the field?

Wolfgang: Integrated optimization-based control systems will be implemented in a complicated multiloop, hierarchical, and decentralized architecture in process and energy systems to effectively cope with the network character of such systems. Only partial coordination of the subsystems of different stakeholders is possible. The models are strongly nonlinear, large scale, and typically characterized by widely varying time scales. The theoretical foundations and the practical issues of engineering and implementing such highly structured optimization-based systems in an industrial environment are largely open. The investigation of these kinds of problems, however, requires us to somehow abandon the traditional view of control systems engineering where the control objective is assumed to be given as a setpoint and some desired control performance. Rather, control has to take a broader view. Its target should be the economic performance of a technical system that is implemented by the plant, the monitoring and automation system, and the human operators and decision makers in face of process and model uncertainty. The integration of various design tasks, such as those related to the process or energy system itself, the operational support system comprising an automatic control and optimization system, as well as the human decision makers, is an obvious challenge to tackle in such a setting.

Q. How did you become interested in process control?

Wolfgang: I remember very well a visit in the control laboratory of E.D. Gilles at Stuttgart University during my undergraduate studies in the first week of the mandatory introductory control course that chemical engineering students take. He showed me a lab-scale chemical reactor operating in a self-sustained oscillatory mode if no controller was active. He then “tamed” the nonlinear dynamics of the reactor by means of a simple feedback controller. This simple laboratory experiment and the clear and enthusiastic explanation of the mechanisms underlying both the open-loop nonlinear
oscillations as well as feedback stabilization left a deep impression and led me to major in systems and control.

Q. You are a recipient of the 2001 Leibniz-Award of the German Science Foundation. Which of your contributions was honored by that award?

Wolfgang: Every year about ten scientists across all the scientific disciplines are honored by the Leibniz award of the German Science Foundation. The award was honoring me for the development and application of systems engineering and computer science methods to the modeling, design, control, and operation of chemical engineering processes.

Q. Please talk a little about the Journal of Process Control (IPC). How would you describe the role of this journal in the process control field?

Wolfgang: The objective of the IPC is to publish papers on the theory and applications in systems and control that are of particular interest to the energy and chemical process industries. Application papers have to go beyond case studies and need to demonstrate novel solution concepts and strategies for a broad class of problems. Industrial implementations of frontier control technologies are also of interest. Theoretical papers constitute an important part of the portfolio of IPC. They have to relate to applications, however. Consequently, such contributions not only have to be original and correct but have to address a problem that addresses a challenging problem in applications. IPC has become the dissemination platform for the latest research results in process control and related fields. The portfolio of papers published vividly demonstrates the high quality of research and activity of the process control community.

Q. Do you see any trends in undergraduate and graduate education relating to process control, especially at RWTH University Aachen?

Wolfgang: The undergraduate education of chemical and mechanical engineers in control should in the first place emphasize modeling and simulation in the context of dynamical systems theory without introducing the concept of feedback in the very beginning. This way, the students can relate the abstract setting of systems and control to the engineering fundamentals in mechanics and thermodynamics. The state space is a natural setting directly resulting from their modeling experience in the mechanics and thermodynamics courses. Then, feedback and control system design can gradually be introduced, ideally integrating time-domain and frequency-domain methods. Systems and control has to be understood and taught as an engineering science rather than a topic in applied mathematics without losing the sound theoretical basis.

Unfortunately, in many universities—including ours—the students largely consider the control course a hurdle to be overcome on their way to the degree rather than a fascinating and relevant topic for practicing engineers. It is this mindset that any undergraduate education in control has to change to get a higher proficiency of practicing engineers in systems and control engineering. I consider this more important than optimizing the curriculum for the systems and control experts. For these students, there is not just a single road to heaven. We have much more interesting and relevant material to teach than the students can digest. A selection with a focus on the fundamental concepts and relevant application classes is required. This selection can and always should reflect the special research expertise of the instructor—following Humboldt’s principle of the unity of education and research.

Q. What courses do you especially like to teach?

Wolfgang: I like most to teach a systems-theory-centered introduction to modeling and simulation for undergraduate students, advanced modeling of chemical and energy process systems, and applied numerical optimization.

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

Wolfgang: I like to listen to all kinds of music. But I am also practicing music. For some years now, four of my chemical engineering colleagues and I have formed a cast (VT5) practicing and performing a cappella cabaret. With our songs and presentation we make fun of ourselves, our profession, the university, and the political and societal system. We have had a number of performances at conference dinners and in the university to entertain colleagues and—in particular—students. It’s been a lot of fun and so different from what all of us are doing professionally.

Q. Thank you for speaking with CSM!

Wolfgang: You’re most welcome.