In this issue of IEEE Control Systems Magazine (CSM) we speak with Prof. Lucy Pao of the University of Colorado. Lucy is active in both the American Automatic Control Council (AACC), as program chair of the 2004 American Control Conference (ACC), and the IEEE Control Systems Society (CSS), as a member of the Board of Governors. CSM spoke to Lucy about her diverse research interests and numerous organizational activities.

CSM also spoke with Bill Geisler of General Electric Company in Loveland, Colorado. As hydro controls product line manager, Bill has marketing and commercial responsibility for the Hydro Controls product line in GE Energy. CSM spoke to Bill to learn more about GE’s role in global power generation projects.

CSM introduces Vikram Kaplia as the corresponding editor for new products.

CSM: Thank you for speaking with IEEE CSM. I can see from your many projects that we have a lot to talk about!

Lucy: It will be a pleasure! I always look forward to the latest issue of CSM, but I never imagined being interviewed in the “People in Control” column.

Lucy: One of the first faculty members I met when I arrived at Stanford was Prof. Gene Franklin, who was assigned to be my undergraduate academic advisor. When I enrolled in the undergraduate signals and systems sequence, it turned out that Gene Franklin wasn’t going to be teaching it that quarter, but instead Martin Hellman was the instructor. So most of my undergraduate-level understanding of signals, systems, and feedback came from Prof. Hellman, who was an excellent teacher.

Having been a transfer student to Stanford, and Stanford being such a wonderful place, I wasn’t quite ready to leave after my senior year there. I stayed on at Stanford for graduate school, where Gene Franklin became my Ph.D. advisor. I took digital control with Prof. Franklin, and control courses from professors Arthur Bryson, Stephen Boyd, and Thomas Kailath. I spent the summer between undergraduate and graduate school at Hughes Aircraft Company (which had been bought by General Motors a few years prior), working on antilock braking and active suspension projects. I spent the summer after my first year of graduate school working at AT&T Bell Laboratories on a robotic hand project. These experiences, along with the challenging and intriguing courses I took at Stanford, convinced me just how interesting and interdisciplinary controls systems could be, and I was hooked.
CSM: My impression is that your Ph.D. research focused on hard disk applications. CSM has published a lot on that topic, especially the history paper by Danny Abramovitch and Gene Franklin. Is there anything you wish to add to what they’ve written on that subject? What really would like to know (for my personal stock investments) is whether you believe that cheap RAM will make hard disks obsolete.

Lucy: My Ph.D. research was on developing robust and near time-optimal controllers for flexible structures. One major application was certainly hard disk drives. Danny and Gene did an excellent job on their CSM disk drive history paper, and it was great to see them win the CSM Best Paper Award. As their article indicates, there are many challenging control problems with hard disk drives. The disk drive control problem that I dealt with is the seek control. Since the read-write arm is not perfectly rigid, and since users desire “seeks” to occur quickly, the resulting “fast” actuator commands often excite the flexible modes of the read-write arm. These problems occur in many types of flexible structures, ranging from the highly flexible structures used in space applications to robotics to information storage systems such as disk drives and tape drives. In high-density tape drives, on which I have also worked, the trend is toward thinner and thinner tape media to allow more data to be stored in a given volume. The thin tape media is essentially a flexible structure.

I’m hesitant to give you financial advice, so, to be a little more secure in my answer, I checked with one of my graduate students, Brian Rigney, who works in the disk drive industry. There are many groups pursuing solid-state RAM as a storage solution, and it is a threat to disk drives but currently only in low-capacity markets. Solid-state RAM is a competitive solution, in both price and performance, for applications such as portable music players, cell phones, and even laptops. Disk drives still hold an extreme advantage in the high-capacity markets, such as disk array server storage, high-end desktop computing, and multimedia applications requiring storage of streaming audio and video. There is no technology on the near-term horizon that can achieve these large capacities (>200 GB) at a price competitive with disk drives.

CSM: You seem to be quite active in haptics. How is that field progressing? What do you view as the critical advances needed in that field? Is the field on the verge of mushrooming?

Lucy: Despite popular belief, haptics involves more than the tactile receptors of your skin. In particular, haptics involves kinesthesia, the sensation of joint motion and acceleration. For instance, when using a hammer, you know that you’ve hit the nail not only from the pressure on and shearing of your tactile receptors in your hand but also from the joint motion sensors in your wrist, elbow, and shoulder. Now, a haptic interface allows users to feel, touch, and manipulate remote or virtual objects. A simple example of a haptic interface is a force-reflective joystick, which not only allows users to manipulate a virtual object on a computer screen but also allows the user to feel the forces that the virtual object experiences when the object collides with other virtual objects. The quality of the force feedback can range from simple vibratory feedback to high-fidelity six degrees-of-freedom (DOF), or 6-DOF, x-y-z force, and roll-yaw-pitch torque feedback.

The field of haptics is growing, and various haptic interfaces have been used in the gaming, automotive, and other industries where vibratory or force information is fed back to a knob or handle held by the user. Higher quality 5- or 6-DOF haptic interfaces have also been developed, and several research groups and companies are exploring applications in surgery, computer-aided design, and scientific visualization where the availability of multi-DOF haptic feedback is important. Currently, high-quality 5- or 6-DOF haptic interfaces are quite expensive (on the order of US$50,000). Therefore, for use in broader applications, it is necessary to develop low-cost yet high-quality multi-DOF haptic interfaces.

Another important issue is the need to improve our understanding of human haptic perception. Much more is known about human visual perception in terms of guiding the development of visual displays. For instance, it is known that having screen refresh rates higher than 80 Hz is not really needed, since few humans can distinguish between a refresh rate of 80 Hz and one of 200 Hz. Hence, there is no need to have a higher-quality visual interface.

There is certainly knowledge regarding perceptual limits in haptics, but how humans interact with haptic interfaces is so complex that much still remains to be learned about human haptic perception in regard to high-end haptic interfaces. What we do know is that the requirements for haptic interfaces that are dictated by human haptic perception are very difficult to meet. Vibration sensitivity in the fingers increases with frequency up to about 300 Hz and then decreases. This frequency dependence indicates that the closed-loop, force-tracking bandwidths in haptic interfaces should be at least 300 Hz, which means that the sampling rates need to be at least 3 kHz. Consequently, sampling, computing Jacobians, calculating the required forces and torques, and other calculations depending on the application must be done for a 5- or 6-DOF interface at rates higher than 3 kHz in a low-cost manner. Of course, the controller must also be designed with a highly variable human-in-the-loop who is holding onto the haptic interface and may do so tightly or loosely, leading to a very different dynamical system in each case.

Until haptic interfaces are sufficiently low cost to be easily accessible and high quality enough to be useful in diverse applications, such interfaces will not be widespread. My colleague Dale Lawrence and I have been collaborating on several haptic interface projects over the last ten years. We
have developed haptic interfaces, carried out user studies to better understand some aspects of human haptic perception, and investigated the use of combined visual, haptic, and audio interfaces in scientific visualization. For example, we are interested in knowing whether users can more effectively understand large, complex, multidimensional data sets such as vector and tensor fields by both seeing and feeling the data rather than only seeing the data.

One of the main foci of our current work is to address the gap in low-cost-yet-high-quality haptic interfaces. Looking at currently available, but very expensive, high-end 6-DOF interfaces, it is clear that much of the cost of such interfaces is in the high-end components (six actuators/motors and six encoders). So we wondered whether it would be possible to use low-cost components and still obtain a sufficiently high quality interface by compensating for the lower-performance hardware components through signal processing and control methods. In doing so, we’re taking advantage of the existing, though still limited, knowledge on human haptic perception. The hope is that ultimately, if the price is reasonable, users will want haptic interfaces as part of their desktop computers.

In this direction, we have recently demonstrated that a low-cost stepper motor and a low-resolution (50-line) optical encoder, together with high-speed digital signal processing, can achieve high torque levels with low ripple as well as accurate position and velocity sensing. While more involved electronics and signal processing are required, the cost of these components continues to decrease compared to the cost of motors and sensors, making the overall design feasible and economical. We have also developed a novel bow spring and tendon actuator design for a haptic interface that provides high-bandwidth force transmission to the fingers, with a large range of motion. The combination of the bow spring and tendon actuator with the low-cost stepper motor and low-cost optical encoder should lead to low-cost haptic interfaces that are also quite compact (in terms of footprint).

We have a 1-DOF working prototype, which we’re extending to a 5- or 6-DOF prototype over the next year. We hope that this work will bring haptic interfaces one step closer to being more widely used. Numerous applications exist in rehabilitation and education, areas which usually do not have large amounts of money to invest in expensive equipment.

CSM: Thanks for that tutorial on haptics! To change the subject slightly, your Subaru Teaching Excellence Award shows your dedication to teaching. Do you have a philosophy that guides you?

Lucy: I really enjoy teaching and interacting with students. I think one of the main philosophies that guides me is to care about the students. I always try to learn the names of all the students in my classes (though sometimes it takes a few weeks in large classes). By getting to know them to at least this small extent, I usually find that I’m more in tune with their expressions (thank goodness not always blank) during class, and I can address them directly if they seem to be puzzled.

I’ve also had fun trying out some new educational technologies. Two new methods I’ve tried over the last year are “clickers” and a digital capture tool.

CSM: What do you mean by “clickers”?

Lucy: It’s always challenging to teach large core (required) courses. In required courses, there are always a few students who are not interested in the material and are taking the course only because it is required for their major. In a large course, it is difficult for the instructor to have a sense of whether students are following a discussion or lecture, since many students are generally too shy to ask questions in larger classes. I tried using “clickers” for my first time in our ECE junior core course on signals and systems. Clickers are personal infrared transmitters that help instructors of large classes gauge the classroom understanding. Instructors ask multiple-choice questions, students respond using their clickers to register their answer, and then the instructor can assess whether the
students understand the material well or whether there are conceptual gaps in their understanding.

At the University of Colorado at Boulder (UCB), clickers are regularly used in the freshman physics, chemistry, and calculus courses, where the enrollments are very large (500+). At UCB, clickers were rarely used in junior-level courses, but I decided to try them in spring 2005 and found them to be quite useful in gauging the students’ understanding of important concepts. Student comments also indicated that they felt more engaged, and I certainly felt that there were more questions and discussion during lectures than when I had previously taught the same course. (More information about clickers can be found at http://www.colorado.edu/physics/EducationIssues/HITT/HITTDescription.html).

I also tried another educational technology tool when I taught our graduate digital control course. Because practicing engineers often enroll in digital control courses, this course is offered not only in a classroom on campus but also at the UCB Center for Advanced Engineering and Technology Education (CAETE) network to engineers around the United States. In Fall 2004, I tried UCB CAETE’s digital capture tool. This tool allowed everything I wrote down to be digitally captured (along with video and audio of the lecture) and made available through the Web to all on- and off-campus students. Most of the students in the course liked this tool, which enabled the students to easily download lectures.

Teaching college courses certainly has changed quite a bit with technology!

**CSM:** As a woman, you’re clearly active in organizations that help support women in developing their careers. How do you view the climate changing with regard to opportunities for women?

**Lucy:** I’m very happy to see more and more women at conferences, which indicates that more women are entering our field. Overall, I believe that the climate is slowly changing and improving for women. I do want to emphasize the word slowly though, and the slowness is sometimes frustrating. However, since most changes are cultural, time is needed for change to occur. On the whole, I think that the environment is generally pretty good. Most policies, decisions, discussions, and comments do not overtly cause trouble for women. However, there are often subtle issues and comments that cause women some trouble or frustration. These issues and comments are almost never meant to hurt women, but because of the slowness of cultural change, sometimes such inadvertent comments or incidents do occur. For instance, on my hallway of the Engineering Center office tower, I am the only woman faculty member. When my colleagues and I have our office doors open, I am much more often interrupted by visitors or students asking for directions or to use my stapler. I believe this situation occurs due to the fact that students and visitors are more likely to think that I’m an administrative assistant than a professor.

There are, however, blatant issues that come up from time to time, and these can be difficult to deal with. One of the larger issues that affected me was when a program manager called a review meeting to be held while I was pregnant with my second child. The location of the program review meeting required that I travel by air, and the timing of the program review was two weeks prior to my due date. My physician’s medical recommendation was not to travel within three weeks of my due date, and airlines policies generally do not allow pregnant women that close to their due date to fly. Nonetheless, it was necessary to negotiate for over two months with the program manager to “allow” me to not physically attend that program review (I ultimately attended by videoconference). Needless to say, that was a stressful experience, which required delicate negotiation with a tough program manager who had a reputation for cutting off funds to principal investigators. I was a junior faculty member at that time, and the possibility of angering a program manager and having my funds cut off was a major concern. I was pleased to hear a few years later that another pregnant woman researcher in that program was allowed to not physically attend the program review meeting without the hassle I experienced.

Clearly, major and minor issues do continue to arise. However, with some effort and persistence on everyone’s part to improve the climate, progress can be made.

**CSM:** One of the challenges of the CSS is to increase its global inclusiveness. Do you have any ideas on how that can be accomplished?

**Lucy:** This inclusiveness is a tough challenge . . . I think that your efforts to highlight control conferences held in countries around the world has been a good step. Other ideas include occasionally having feature articles on industrial control issues that are dominant in various countries or regions. I agree with Rick Middleton, whom you interviewed for the June 2005 “People in Control” column, that the CSS sometimes inadvertently operates in a U.S.-centric mode. I asked some of my current and past research students their thoughts on this matter, and one of their suggestions was to create an online directory of CSS members working in various areas of control. While most researchers and engineers at universities have Web pages, those in industry usually do not (and, hence, they don’t always turn up on Google searches). Such an online directory might provide a way to improve our networking with those across the globe.

**CSM:** Thank you for speaking with CSM!

**Lucy:** It was my pleasure!
Bill Geisler with his wife Erika at the Great Sphinx in Giza, Egypt. Bill travels worldwide as GE Energy’s product line manager for Hydro Controls.

CSM: Thank you for speaking with CSM. Before I ask about the various projects you’re involved in, I was wondering if you could tell me about your engineering education and experience.

Bill: Although I do not view myself as a control engineer, I work extensively with control engineers from across GE. I have a bachelor’s degree in engineering physics from Rensselaer Polytechnic Institute (RPI) in Troy, New York. Engineering physics is essentially a combination of electrical and mechanical engineering, with a nice dose of physics added in. I have my master’s degree in nuclear engineering, also from RPI.

I became interested in engineering because I enjoyed solving problems and I enjoyed tearing apart electronics, figuring out how they work, and putting them back together to work better. For example, when I was about ten years old, I took apart a Star Trek walkie talkie, found a power supply on my dad’s workbench, and hooked it up to the roof antenna—I jacked up the power and talked to my dad three miles away!

Related to my experience, I started off as a semiconductor engineer with IBM before I came to GE. I have been in the power industry for 15 years and have lived all over the country and worked all over the world. Working in GE Energy has given me the opportunity to work on large electrical power projects in fossil, nuclear, and, of course, hydro plants. Control solutions is one of my favorite areas because I get to look at the interconnection of hundreds of components that make a working system.

CSM: What are your responsibilities at GE?

Bill: I am the product line manager for our Hydro Controls product line. This position is a combination of marketing, new product development, and product support.

CSM: What kinds of control-related technology is GE involved in to support hydropower?

Bill: Our technology in control spans a breadth of applications. We offer control solutions for both new units and for retrofit projects that include custom-engineered digital control systems in simplex, duplex, and triplex redundancies; mechanical products, including the FC20000 flow control valve; plug-and-play upgrades to enable digital functionality without a traditional control upgrade; excitation control for all types of hydro turbines; and application support, installation, and commissioning as well as start-up services.

CSM: The Three Gorges project is one of the largest engineering projects in history. Can you give us some sense of scale and scope in a project of this type?

Bill: Launched in 1993, the Three Gorges Project is being built on the middle reaches of China’s longest waterway, the Yangtze River. When it is completed in 2009, the Three Gorges Project will consist of 26 generators with a combined energy generation capacity of 18,200 MW and will be able to generate 84.7 billion kWh of electric power annually. This project is one of multiple contracts that GE Energy has recently won in conjunction with China’s Gas Turbine Power Plants Construction Project.

CSM: What kinds of control-related innovations is GE developing to make Three Gorges a success?

Bill: GE developed a customized control solution for Three Gorges. We combined a Woodward MicroNet triple modular redundant (TMR) electronic controller with proprietary algorithms integrated with the FC20000 flow control valve. This control solution will have the capacity to process 23,700 l/min at 1,100 psi.

CSM: What are some of the technological challenges of the project from a control point of view?

Bill: For a unit the size of Three Gorges, the biggest challenge is valve control. The sheer size of the unit makes it challenging to turn on/off the unit without wasting...
New Corresponding Editor

IEEE Control Systems Magazine is pleased to announce that Vikram Kapila has been named corresponding editor for new products. Vikram received the B. Tech. degree in production engineering and management from the National Institute of Technology, Calicut, India, in 1988; the M.S. degree in mechanical engineering from the Florida Institute of Technology, Melbourne, Florida, in March 1993, with specialization in dynamics and control; and the Ph.D. degree in aerospace engineering from Georgia Tech in 1996, with specialization in flight mechanics and control. In September 1996, he joined the faculty of mechanical engineering at Polytechnic University, Brooklyn, New York, where he has held the rank of associate professor since 2002. He is the director of the Web-Enabled Mechatronics and Process Control Remote Laboratory, an National Science Foundation-funded Research Experience for Teachers site in mechatronics, and an NSF-funded GK-12 fellows project. Dr. Kapila has held visiting positions with the Air Force Research Laboratory in Dayton, Ohio. His research interests are in cooperative control; distributed spacecraft formation control; linear and nonlinear control with applications to robust control, saturation control, and time-delay systems; closed-loop input shaping; spacecraft attitude control; mechatronics; and DSP/PC/microcontroller-based real-time control. He received Polytechnic’s 2002 Jacob’s Excellence in Education Award and a 2003 Distinguished Teacher Award. In 2004, he was selected for a three-year term as a Senior Faculty Fellow of Polytechnic University’s Othmer Institute for Interdisciplinary Studies. He has edited one book and has published more than 100 journal and conference articles.