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Balancing act

Rick Nelson, Chief Editor -- 3/1/2005
Test & Measurement World

In our September 2004 issue, we profiled the accomplishments of six outstanding test engineers from various industries, and we asked our readers to vote for the Test Engineer of the Year. Your choice? Anthony Levandowski.

As part of his award, Anthony will designate an engineering school to receive a \$20,000 education grant, courtesy of National Instruments, the award sponsor.

BERKELEY, CA. Riding a bike is easy. But learning to ride, or teaching someone else how to ride, is hard. Anthony Levandowski and his GhostRider Robot team are tackling a much bigger challenge—teaching a motorcycle to drive itself.

The immediate goal is a strong showing in the October 8, 2005, DARPA Grand Challenge, which requires that an autonomous vehicle traverse up to 175 miles of terrain in the southwestern US in less than 10 hours. Levandowski is pursuing a two-wheeled approach that differentiates his UC Berkeley-based team's entry from the Hummers and other four-wheeled and even six-wheeled vehicles entered by other teams.

In the first competition, held in March 2004, no vehicle got farther than 6 miles, and a combination of equipment failures and human error kept the GhostRider team's entry in the starting blocks. "It wasn't our finest moment," said Levandowski of his team's showing, but it was a moment that spurred on a marathon effort that will culminate with participation in the October 8 event. The team is taking several steps to improve reliability and minimize the opportunities for human mistakes.

A lifelong fascination with technology has brought Levandowski to the point where he now devotes 14-hour days to the autonomous-motorcycle project. An early love of Legos plus a desire to become a robot designer, he said, were early indicators that he would pursue engineering. And pursue it he does, to the point where his work vs. leisure time balance isn't quite as good as his motorcycle's balance: "When I'm not working, I'm sleeping."



Navigating the course

All the effort is going into optimizing his vehicle by the October 8



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event. A successful vehicle must be able to navigate a course defined in a data file that DARPA will provide 2 hrs before the event begins (see "The challenge," below). Getting the course details so late turns out to be the easy part—ideally, guided by GPS satellites, straight-line navigation between waypoints defined in the file would lead inexorably to the finish line, but natural and manmade obstacles along the course severely complicate the task.



Even straight-line GPS navigation isn't foolproof, though, Levandowski said. "GPS has been very interesting. We've found that GPS accuracy is sensitive to weather, time of day, and other factors that I can't measure or see, like storm conditions in the ionosphere that interfere with the satellite signals. Relying solely on GPS, a vehicle might believe it has suddenly shifted 2 m to the right, prompting it to attempt corrective action that puts it in a ditch on the left. I think last year that's what killed some of the other teams—they had absolute positioning errors, and the localized sensors weren't integrated well.

GPS variability combined with the obstacles—including boulders, ditches, fences, shrubbery, power-line pylons, other vehicles, and World War II-era tank traps placed by DARPA personnel—make it necessary for the motorcycle to have a sensing system that detects the immediate environment along the course, which includes unpaved trails and fire roads. DARPA designs the course so that a human in a 4x4 pickup truck could traverse it easily. But while a human can easily recognize obstacles, getting machines to sense and detect real-world contours is very difficult.

Fortunately, said Levandowski, "We don't have to be able to determine whether something is a power pylon or another vehicle; instead, we take a more general approach, attempting to divide the field of view into a group of 6-in. polygons that our algorithm can recognize as an obstacle or a feasible path for the vehicle. We can't just work from a point cloud—there are too many possibilities and too much computation to be done in real time. We can't have the vehicle stop and look around and calculate for 5 min before going on. There is really an emphasis on speed here—you have to be able to average 15 mph, which is not trivial."

The technology exists today to complete the course (using lidar mapping, for example), he said, but it would require three or four days.

Machine vision

The GhostRider team's object-recognition scheme relies on a two-camera system, with the cameras mounted on gimbals to keep them level and looking forward, no matter the attitude of the bike. That orientation makes it easier for the image processor to correctly analyze the scene. A lot of teams are using a two-camera system, he said, but added, "We have a different approach in that our implementation uses hardware FPGAs [Vertex 2000e and Vertex 2P 100 from Xilinx]. Our algorithms are a little bit simpler but run much faster, letting us get a lot more computation done to analyze the terrain in front of us."

The team considered image-sensing alternatives, including lidar, ultrasound, and radar. Lidar, he said, is too slow and expensive, while ultrasound doesn't have sufficient range, permitting top speeds of only 7 mph. As for radar, "It kept getting feedback off flies or something and was absolutely unusable."

In addition to cameras, the vehicle includes two main logic boxes: One—the FPGA sensor hub—handles the sensor signal processing; the other—the emergency-stop (e-stop) board—handles power distribution, motor control, and signal monitoring and filtering. The e-stop board employs 10 solid-state relays and 10 mechanical relays and is designed to act as the robotic watchdog for the entire vehicle, able to automatically start up and shut down the big subsystems in the proper sequence so there's no need for interaction.

That's important. On race day, contestants have just 5 min to power-up their vehicles, placing them into a "pause" state, ready to begin the race any time within the next hour (5 s after receiving a run signal from DARPA Grand Challenge officials). In the 2003 challenge, the team had to perform the startup sequence using manual switches, and the active stabilization subsystem remained off, keeping the bike at the starting line.

Sensors include two cameras, 12 optical encoders, a GPS unit, and two inertial measurement units, each of which contains three accelerometers and three gyros, with one adding a three-axis magnetometer. "The IMUs serve as the equivalent of the inner ear of the vehicle," said Levandowski, "providing roll,



pitch, and yaw information plus x, y, z acceleration data. Kalman filtering and integration provide stabilized roll angle and pitch angle, and the magnetometers provide yaw information."

The team employs two IMUs, provided by Crossbow Technology, in part to provide redundancy. "We can afford to lose one but not two, so the e-stop board allows us to reset one independently if it starts giving us funny readings. We also use two IMUs for error checking. We need more than just current roll angle—we need to know the error bounds. Much of the testing we do is going into understanding with high precision and a high confidence level how the vehicle is oriented right now so we can achieve the stability that we need."

Based on sensor inputs, the FPGAs and onboard computers—two 586-class low-power boards from AMD—make decisions and deliver commands to the actuators that drive various motors, including ones that control the bike's brakes, throttle, steering, sensor gimbal, and a self-righting arm that allows the bike to pick itself up should it fall over. The low-power computers are key, he said. "More processing capability is always nice," he said, "but we have a 150-W power limit for the onboard electronics, and the 1.5-GHz processors we chose use only 6 W each."

During the Grand Challenge event, teams are forbidden to establish wireless contact with their entry, and in fact, the vehicles themselves may not use wireless approaches for onboard communication among various subsystems. For test purposes though, the GhostRider team has found it useful to use a wireless link to monitor test data and provide test inputs. Because the vehicle employs Ethernet for onboard data communications, the team was easily able to implement a WLAN interface that permits control of the moving vehicle from a laptop. "This remote control allows us to interject our own commands for simulating different kinds of environments," said Levandowski. "It lets us simulate certain events such as a yaw-angle problem, a steering error, or GPS drift."

Learning of the challenge

Belgian-born Levandowski first heard about the DARPA Grand Challenge from his mother, who came across a mention of it in her work at the European Union. Knowing of his longstanding interest in robotics, she e-mailed him the item. "I knew immediately that was something I really wanted to be part of," he said. "It just totally clicked. How could I resist? Now, I put in 14 hours a day and it's so much fun I forget that I'm here."

Levandowski arrived in the US at age 14, able to speak English (having learned from his English-speaking father) but not write it. A quick study, he as a high-school freshman enrolled in a computer-science class at Marin County Community College near his home. There, what struck him as different from Europe was that people were judged by their skills, not who they knew or how old they were.

As an undergrad at Berkeley, his early interest in Legos paid off with his first Challenge victory. He entered the Sun Microsystems-sponsored inaugural Java Technology Lego MindStorms Challenge. His winning entry was BillSortBot, an electronic Lego-based contraption that sorted Monopoly money by color.

But despite this success, he described his robotics experience as limited. "Large-scale things that move around on their own—I've never done anything like that before." His undergrad and graduate degrees in industrial engineering had taught him how to run a project and identify problems, he said, but he didn't have much experience with disciplines like control theory or with many of the mechanical and electrical subsystems involved. "I had to bring in people who were really good at each of these systems and get them to work together and test the results."

The GhostRider team's home is on the UC Berkeley campus, where Levandowski earned his bachelor's and master's degrees in industrial engineering. Now, he defines his official position at the university as "squatter." He said that, since earning his master's degree in May 2003, "I spend full time—about 80 hours per week—on the robot project. I am thinking about going back for a PhD, but I'm not currently officially affiliated with the university."

Berkeley and the project

"In general, the university has been very receptive to the project at the higher levels, but it's difficult getting a faculty sponsor to actually acknowledge that this could be done," he said. "Faculty members don't want to take risks. If you're looking for tenure, you don't want any bumps on your record and would want to avoid the embarrassment that failure in this high-visibility project would entail." Therefore, he added, Berkeley's contribution thus far is the lab space the team uses on campus.

Even those humble digs were long in coming: "It took a year. Last year, the vehicle was built in my garage. It's sad on some level that it took so much effort just to do that. Even if the project is not successful, it's good for students to get involved in something where you have to get something to work and there's a deadline, and you have to work with different disciplines, like mechanical, electrical, and even civil engineers."

Frank Wang, a team member and a junior studying EE, concurred. "It's gratifying to work on this project. It's a good environment for me to grow in," providing a vivid lesson in the reliability of



hand-soldered connections (used extensively in the 2003 motorcycle version) vs. the increased use of PCBs in the newer version. Just learning the importance of test points was huge, he said.

Wang learned about the project in a Slashdot article. Berkeley, he said, doesn't have a strong robotics program for undergraduates, and the project gives him a chance to focus on a discipline that's held his interest since high school.

Like Wang, most of the GhostRider team members are Berkeley students. The exception is a graduate student at Texas A&M, who is working on the vision algorithms. That student's professor is a former graduate-school classmate of Levandowski. The Berkeley students thus far haven't received credits for working on the program, Levandowski said, adding that the paperwork is in process to arrange credits for at least Wang.

Instruments and funds

Along with getting support within the university, he said fundraising has been a major problem. "My savings are going fast. I got really lucky in that I started a business before the dotcom boom ended and made a small amount of money that let me buy a house and put about \$120,000 dollars of my own cash into the project so far. AMD has contributed a good chunk—about \$40,000 in 2004, and AMD and Raytheon contributed in 2003. But it's been difficult to find a big donor."

He hopes that improves: "Last year, we were starting from scratch, and no one knew who we were or what we were doing. Now, people have heard of us, and this year we expect to be competitive.

Because funding has been a problem, the availability of instrumentation has, not surprisingly, also been a problem. "There's a lot of fancy equipment here on campus that's used maybe 10 hours per year, but it's not available to us." The team has received donations, including a logic analyzer and several Agilent Vee licenses from Agilent Technologies and data-acquisition hardware from National Instruments. Levandowski is expecting to receive digital Camera Link cameras from Dalsa to replace the USB webcams he's been using. "The webcams at 10 frames per second are too slow."

The logic analyzer was critical, he said: "We couldn't have done any of the FPGAs without it—each has 160 signal lines to debug." And, he said, NI's daq cards were useful in evaluating a radar-based sensor scheme, which the team ultimately rejected in favor of the cameras.

Nevertheless, Levandowski has a wish list: "We already have a scope, but it's older than most team members, and we could use a replacement." He also said the team needs two lab power supplies, three multimeters, and a function generator.

What are the prospects for success? "We are hoping to win, but realistically, I don't think that's in the stars right now. We want to finish in the top five." Not anticipating the \$2 million payoff, he hopes ultimately to turn his robotics work into a paying job in the form of a research contract or by spinning off one or two components the team has developed.

Regarding the challenge, he said, "I don't think success is actually attainable by anyone this year except for the team from Carnegie Mellon, which is perhaps the premier robotics university in the world." That team, he said, has 40 grads and 40 undergrads working on the project plus many millions of dollars in funding.

His goal, he said, is to "try to get the vehicle through the race, and if we can make it in 20 hours, that would be fantastic. Our winning the 2 million bucks is very unlikely. If I were trying to make \$2 million in one year, I'd find an easier way. This is an expensive game, almost like the America's Cup. The prize will not compensate you financially for what you put in."

The challenge

The DARPA Grand Challenge will take place October 8, 2005, in the desert Southwest. The route will be no more than 175 miles over desert terrain featuring natural and manmade obstacles.

Two hours before the event begins, participants will receive a CD containing a route-definition data file, which will define a corridor in which the successful vehicle must remain while traversing the course in less than 10 hours. The file contains waypoints, lateral boundary offsets, and maximum speed limits.

The winner is the team that finishes in the quickest time less than 10 hours. The award is \$2 million.

For more, see www.darpa.mil/grandchallenge

Why two wheels?

Here are five of the top six reasons to build an autonomous motorcycle, according to Anthony Levandowski and Frank Wang of the GhostRider Robot team:

6. "We couldn't afford a Hummer."
5. "We didn't have access to lab or outdoor test space that could accommodate anything much larger than 6 ft in length."
4. "Four-wheeled vehicles offer much less opportunity for innovation."
3. "We would have had no opportunity to get funding if we had arrived on the scene as the 20th or 30th team entering a four-wheeled vehicle."
2. "A riderless motorcycle is cool."



But the number 1 reason, said Levandowski, is this:

"Ultimately, a two-wheeled vehicle, because of its narrow profile, will be superior to a four-wheeled vehicle in the applications DARPA is interested in. It will be more efficient to bring the lightweight two-wheelers to their deployment points, and once deployed, they'll be able to go more places faster than any larger vehicle. If we are racing across the desert, and I'm on a motorcycle and you're in a Hummer, I'll always win."

For more on the project, including videos of the autonomous robot in action, see www.ghostriderrobot.com.

The autonomous future

What's the future look like for autonomous vehicles? For Anthony Levandowski's take, see "[The future—autonomous and otherwise—and the past.](#)"

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