


INNOVATIONS FROM A ROBOT RALLY

By W. Wayt Gibbs

This year's Grand Challenge competition spurred advances in laser sensing, computer vision and autonomous navigation—not to mention a thrilling race for the \$2-million prize

THE MOST VALUABLE AND COMPLEX component in a modern vehicle typically is also the most unreliable part of the system. Driving accidents usually have both a human cause and a human victim. To certain engineers—especially those who build robots—that is a problem with an obvious solution: replace the easily distracted, readily fatigued driver with an ever attentive, never tiring machine.

The U.S. military, which has been losing soldiers to roadside bombs in Iraq for several years, is particularly keen on this idea. But by 2002 more than a de-



MACHINE ON A MISSION, Sandstorm swivels its laser-scanning "eye" (*inside silver dome*) to peer around a tight turn as it negotiates Beer Bottle Pass in the 2005 Grand Challenge race, followed by a DARPA chase vehicle. The autonomous Humvee drove the 132-mile course at an average speed of 18.6 miles an hour but was bested by a slightly faster robot.

An Endurance Race for Robots

Enthusiasm ran high among the 550-odd engineers from seven nations and 42 U.S. states who gathered in Pasadena, Calif., in August 2004 to hear DARPA officials lay down the rules for the 2005 Grand Challenge race. Many had already set aside day jobs and invested their own savings to begin work on a self-navigating ground vehicle, in hopes of earning a shot at the \$2-million prize in October 2005. Few seemed discouraged by the results of the first Grand Challenge, held on March 13, 2004, when only 13 teams were able to field machines for the 142-mile course and none cleared the first mountain crossing [see "A New Race of Robots," by W. Wayt Gibbs; SCIENTIFIC AMERICAN, March 2004].

Sandstorm, constructed by the Red Team at Carnegie Mellon University, had traveled fastest and farthest in the 2004 event, driving at up to 36 miles an hour before straying off the edge of a narrow hairpin turn 7.4 miles into the route. But even as it fell far short of the goal, Sandstorm's performance set new records in off-road robotics and ignited the imagination of many of the roboticists, students and backyard mechanics here.

Ron Kurjanowicz, the DARPA program manager for the 2005 Grand Challenge, spelled out the rules. Any kind of traction-propelled vehicle could enter, but officials would disqualify any robot that interfered with another, damaged the environment or communicated with humans in any way during the race. The course, delineated by a computer-readable list of GPS waypoints, would be held secret until 4 A.M. on race day. "This year you should be prepared to drive 175 miles in 10 hours or less," Kurjanowicz said. The robots will have to negotiate many obstacles, Tether warned. "There are gullies, washouts, stopped vehicles, underpasses, utility towers. And on the morning of the race we're going to place several tank traps on the road," he said, showing a photograph of a scary-looking obstruction built from three crisscrossed iron girders.

"Our job is to look for crazy people with crazy ideas," Tether said, only half in jest, "and then to bring those ideas as quickly as possible from the 'far side' of technology to the near side. Looking at the crowd here today, I'd say we've done that."



MENAGERIE OF ROBOTS in the 2005 Grand Challenge included several that, like Team Cornell's Spider (top), were based on military vehicles. Many entrants adapted pickup trucks or SUVs in order to focus their efforts on inventing new software and sensors, such as Team DAD's 64-laser terrain scanner (middle). And some vehicles were designed from scratch, including Team Jefferson's Tommy (bottom).

cade of military-funded research on autonomous ground vehicles had produced only a few slow and clumsy prototypes.

So that year the Pentagon authorized its Defense Advanced Research Projects Agency (DARPA) to take an unconventional approach: a public competition

with a \$1-million prize. The next February DARPA director Anthony J. Tether announced that the Grand Challenge—the first long-distance race for driverless vehicles—would be held in the Mojave Desert in March 2004. When no robot completed that course, DARPA doubled

the prize and scheduled a second running, through a different part of the desert, for October 2005.

The point of the Grand Challenge was not to produce a robot that the military could move directly to mass production, Tether says. The aim was to energize the engineering community to tackle the many problems that must be solved before vehicles can pilot themselves safely at high speed over unfamiliar terrain. "Our job is to take the technical excuse off the table, so people can no longer say it can't be done," Tether explained at the qualifying event held 10 days before the October 8 race.

Clearly, it can be done—and done in more than one way. This time five autonomous vehicles crossed the finish line, four of them navigating the 132-mile course in well under the 10 hours re-

Overview/*The Grand Challenge 2005*

- Five out of 23 competing robots successfully navigated a 132-mile course through the Mojave Desert in October 2005 as part of the DARPA Grand Challenge race. To qualify for the \$2-million prize, the driverless vehicles had to finish in less than 10 hours. Four turned in elapsed times under 7.5 hours.
- The competition inspired numerous technical innovations that enable computer-controlled vehicles to move quickly over rough and unfamiliar terrain. The robotic entrants demonstrated advances in location tracking, road and obstacle perception, and high-speed path planning.
- These technologies may appear in future military, agricultural, industrial and even consumer vehicles. Some are already being commercialized.

quired to be eligible for the cash prize.

More important than the race itself are the innovations that have been developed by Grand Challenge teams, including some whose robots failed to finish or even to qualify for the race. These inventions provide building blocks for a qualitatively new class of ground vehicles that can carry goods, plow fields, dig mines, haul dirt, explore distant worlds—and, yes, fight battles—with little or no human intervention.

“The potential here is enormous,” insists Sebastian Thrun, director of Stanford University’s Artificial Intelligence Laboratory and also head of its robot racing team. “Autonomous vehicles will be as important as the Internet.”

From Here to There

IF ROBOTICS IS EVER to fulfill Thrun’s bold prediction, it will have to leap technical hurdles somewhat taller than those posed by DARPA’s competition. The Grand Challenge did define many of the right problems, however. To succeed in such a race, vehicles first have to plot a fast and feasible route for

the long journey ahead. Next, the robots need to track their location precisely and find the road (if there is one) as well as any obstacles in their way. Finally, the machines must plan and maneuver over a path that avoids obstructions yet stay on the trail, especially at high speed and on slippery terrain.

Two hours before the event began, DARPA officials unveiled the course by handing out a computer file listing 2,935 GPS waypoints—a virtual trail of bread crumbs, one placed every 237 feet on average, for the robots to follow—plus speed limits and corridor widths. Many teams simply copied this file to their robots unchanged. But some used custom-built software to try to rapidly tailor a route within the allowed corridor that could win the race.

The Red Team, based at Carnegie Mellon University, raised this mission-planning task to a military level of sophistication. In a mobile office set up near the starting chutes 13 route editors, three speed setters, three managers, a statistician and a strategist waited for the DARPA CD. Within minutes of its ar-

rival, a “preplanning” system that the team had built with help from Science Applications International Corporation, a major defense contractor, began overlaying the race area with imagery drawn from a 1.8-terabyte database containing three-foot-resolution satellite and aerial photographs, digital-elevation models and laser-scanned road profiles gathered during nearly 3,000 miles of reconnaissance driving in the Mojave.

The system automatically created initial routes for Sandstorm and H1ghlander, the team’s two racers, by converting every vertex to a curve, calculating a safe speed around each curve, and knocking the highest allowable speeds down to limits derived from months of desert trials at the Nevada Automotive Testing Center. The software then divided the course and the initial route into segments, and the manager assigned one segment to each race editor.

Flipping among imagery, topographic maps and reconnaissance scans, the editors tweaked the route to take tight turns the way a race driver would and to shy away from cliff edges. They

A MOTORCYCLE THAT STEERS ITSELF

1 When not in motion, the motorbike rests on retractable landing gear (a)

2 Guided by microelectromechanical sensors that measure the bike’s orientation, onboard computers steer the front wheel gently left or right to keep the vehicle upright and driving straight (b)

3 To make a right turn, the robot first jerks its front wheel briefly to the left (c), which causes the body to lean over to the right...

4 ... then straightens its wheel as the chassis continues to tip right (d), and finally steers right (e) to halt its fall. The vehicle holds this pose, in which the push of centrifugal force balances the pull of gravity, for the duration of the turn

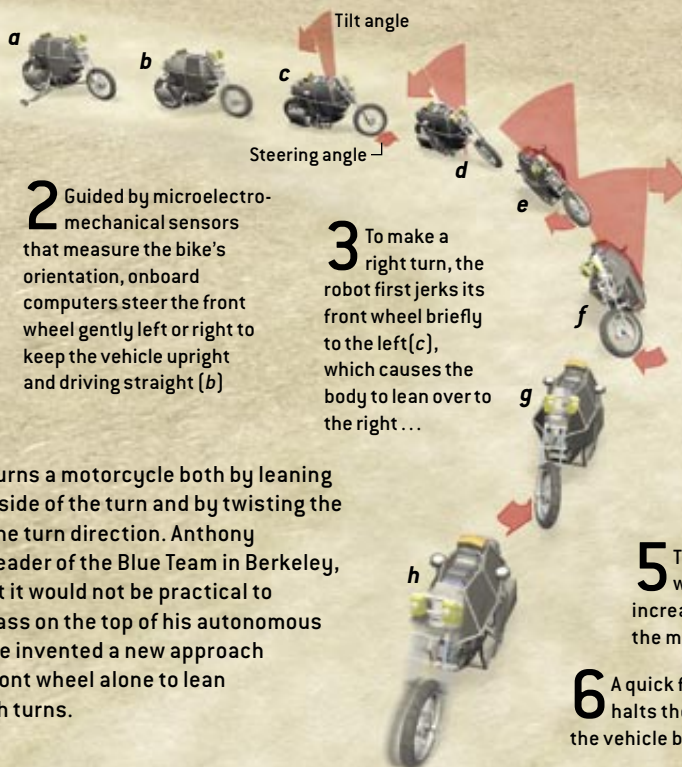
5 To exit the turn, the robot kicks the front wheel even farther to the right (f), which increases the centrifugal force and rights the motorbike

6 A quick flick of the wheel to the left (g) halts the rotation of the chassis and puts the vehicle back on a straight heading (h)

A human rider turns a motorcycle both by leaning weight to the inside of the turn and by twisting the handlebars in the turn direction. Anthony Levandowski, leader of the Blue Team in Berkeley, Calif., knew that it would not be practical to move a large mass on the top of his autonomous motorbike, so he invented a new approach that uses the front wheel alone to lean the bike through turns.



GHOSTRIDER ran unassisted for 20 miles at a time in desert testing.



JOHN KOCCON (illustration); ANTHONY LEVANDOWSKI (photograph)

The Race to the Starting Line

Forty-three robots rolled onto the infield of the California Speedway in Fontana, Calif., on September 28, 2005, for the Grand Challenge semifinals. Over the next eight days, each robot would get at least four chances to run a speed trial through the roughly two-mile course, which officials had cluttered with fence gates, parked cars, stacked tires and a tunnel that blocked GPS reception. Chris Urmson of the Red Team and Sebastian Thrun of the Stanford Racing Team surveyed the competition from the top of the grandstands. As they gazed at the gamut of robots ranging from a 275-pound minibike to a 15-ton military truck, Urmson broke into a grin. "This may be the coolest thing I have ever seen," he said.

The vehicles on display had been sifted from a much larger crop. DARPA accepted applications from 195 groups, including three high school teams, 35 university squads and all 15 finalists from the 2004 Grand Challenge. Many high-powered universities that sat out the first race—including Stanford, Cornell, Princeton, the University of California, Los Angeles, and the Massachusetts Institute of Technology—had entered in the second.

Only 118 teams made the first cut, based on a technical summary and a video of the vehicle in action. In May, DARPA officials visited each team for an on-site inspection and demonstration on a 220-yard (200-meter) zigzag course. The inspectors timed each robot and placed garbage cans in its path to test its obstacle-dodging abilities over three runs.

The more advanced teams sent their robots on a longer fourth run to show off the machines' driving skills. In Cedar Rapids, Iowa, Team Terramax's Oshkosh truck was able to back up and realign its eight-foot-wide body to squeeze around traffic cones with just inches to spare. At an old steel mill site in Pittsburgh, the Red Team's H1ghlander Hummer sped at 25 miles an hour over rubble-strewn road and shot through a railroad underpass.

From the first day of the qualifiers, it was clear that the technology had taken giant strides in the past 18 months. Eleven of the 43 contestants completed the obstacle course on their first try, and 25 robots had done so by the end of the trial—some hitting speeds over 40 miles an hour. Two of the finishers had crashed badly on some of their runs and were eliminated. DARPA sent the remaining 23 on to Primm, Nev., to take their shot at the \$2-million prize.

marked "slow" any sections near gates, washouts and underpasses; segments on paved roads and dry lake beds were assigned "warp speed."

The managers repeatedly reassigned segments so that at least four pairs of eyes reviewed each part of the route. Meanwhile, in a back room, team leaders pored over histograms of projected speeds and estimates of elapsed time. Team leader William "Red" Whittaker ordered completion times of 6.3 hours for H1ghlander and 7.0 hours for Sandstorm, and the system adjusted the commanded speeds to make it so.

Hitting the Road

ROADS CHANGE—desert roads more than most—so no map is ever entirely up-to-date. And even the perfect route is of no value unless the robot always knows where it is and where it needs to

go next. Every vehicle in the Grand Challenge was equipped with differential GPS receivers. They are generally accurate to better than three feet, but overpasses and canyons block the GPS signal, and it sometimes shifts unpredictably.

Most teams thus added other tracking systems to their robots, typically inertial navigation systems that contain microelectromechanical accelerometers or fiber-optic gyroscopes. But two of the competitors created technologies that promise to be more accurate or less expensive, or both.

A team of high school students from Palos Verdes, Calif., found inspiration in the optical mouse used with desktop computers. They installed a bright lamp in their Doom Buggy robot and directed the white light onto the ground through optical tubing. A camera aimed at the bright spot picks up motion in any hori-

zontal direction, acting as a two-dimensional odometer accurate to one millimeter. "We call it the GroundMouse," says team member Ashton Larson.

The Intelligent Vehicle Safety Technologies (IVST) team, staffed by professional engineers from Ford, Honeywell, Delphi and Perceptek, used a similar technique on its autonomous pickup truck. A radar aimed at the ground senses Doppler shifts in the frequency of the reflected beam, from which the robot then calculates relative motion with high precision. Whenever the vehicle loses the GPS fix on its position, it can fall back on dead-reckoning navigation from its radar odometer.

In the desert, even human drivers sometimes have difficulty picking out a dirt trail. It takes very clever software indeed to discriminate terrain that is probably road from terrain that is prob-



CUT: M.I.T.'s Manticore (top) failed its on-site demonstration. IRV, built by Indy Robot Racing, flamed out on the straw bales in Fontana (middle). Team ENSCO was a contender for the prize until its Dexter robot (bottom) struck a boulder in the road at mile 81 of the race.

ably not. Such software, Tether says, “is a big part of what I call the ‘secret sauce’ that makes this technology work.”

The experience of the Grand Challenge suggests that for robots, laser scanners provide the best view for this task. By rapidly sweeping an infrared laser beam across a swath of the world in front of the machine, a scanner creates a three-dimensional “point cloud” of the environment. A single laser beam cannot cover both distant objects and nearby road with sufficient fidelity, however, so a robot typically uses several in concert.

More lasers are not necessarily better. IRV, the Indy Robot Racing Team’s autonomous Jeep, sported 11. But when

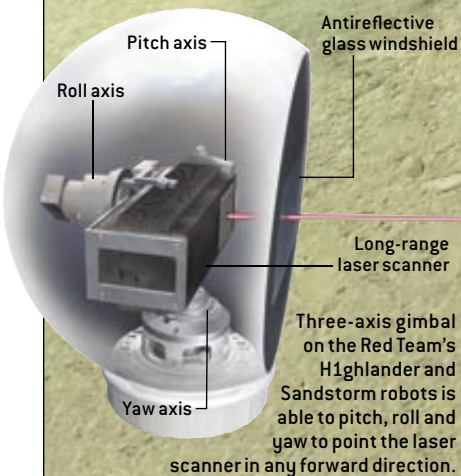
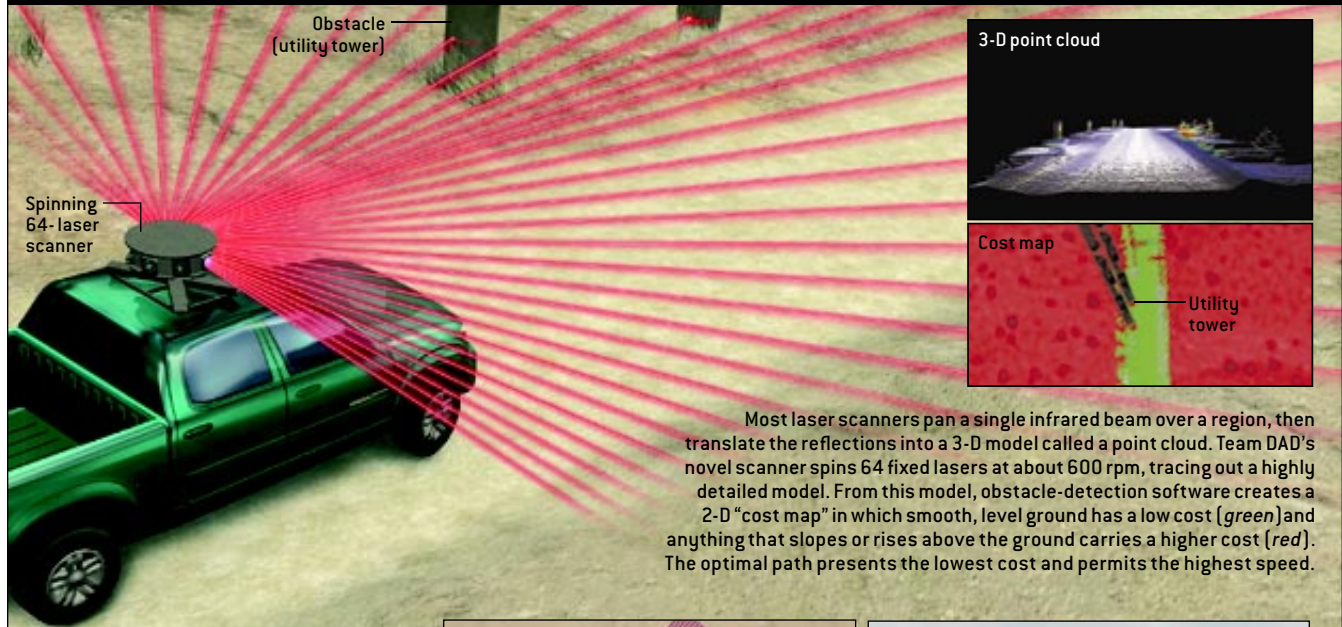
the vehicle’s sensors were knocked out of alignment, it ran over hay bales, caught fire and was eliminated during the qualification round. Without accurate calibration, laser scanners place obstacles in the wrong spot on the robot’s internal map, drawing the vehicle into the very objects it is trying to avoid.

David Hall of Team DAD, a two-man operation from Morgan Hill, Calif., created a novel laser sensor that addresses the calibration problem by fixing 64 lasers inside a motorized circular platform that whirls 10 times a second [see box below]. A bank of fast digital signal processors, programmed in the low-level Assembly language,

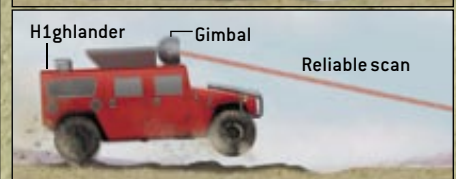
handles the flood of data. In prerace trials, the sensor was able to pick out obstacles the size of a person from up to 500 feet away.

The Red Team took a different but equally innovative approach with its two robots. Each carries a single long-range laser that can do the job of many, because it swivels, rolls and nods on top of an articulated arm called a gimbal. Protected by a dome and windshield that look like a giant eyeball on top of the robot, the laser can tilt up or down when the vehicle climbs or descends. As the robot approaches a turn, the gimbal swivels left or right, keeping its eye trained on the road.

ROBOTS THAT SEE AROUND CORNERS



Hairpin turns are typically blind turns for robots. But DAD, H1ghlander and Sandstorm can often see the other side of a tight curve before they get there. DAD has a full 180-degree field of view; the Red Team robots swivel their gimbals.



Rough roads jostle fixed lasers, creating gaps in the 3-D model. The Red Team gimbal senses such jolts with fiber-optic gyroscopes, then uses its actuators to cancel out the motion. The result is more reliable perception, especially when looking far ahead.

Red Team engineers also mounted fiber-optic gyroscopes to each of the gimbal's three axes and linked them via a feedback system to actuators that stabilize the laser so that it holds steady even as the vehicle jumps underneath it. The team failed to integrate that stabilization capability with the robots' other systems in time to use it for the race. But both Motion Zero, a company just launched by the Blue Team in Berkeley, Calif., and HD Systems in Hauppauge, N.Y., are miniaturizing the technology and planning to market it for use in satellites, weapons systems and camera platforms.

A Path to the Future

INDISPENSABLE AS lasers seem to be, they have their drawbacks. At \$25,000

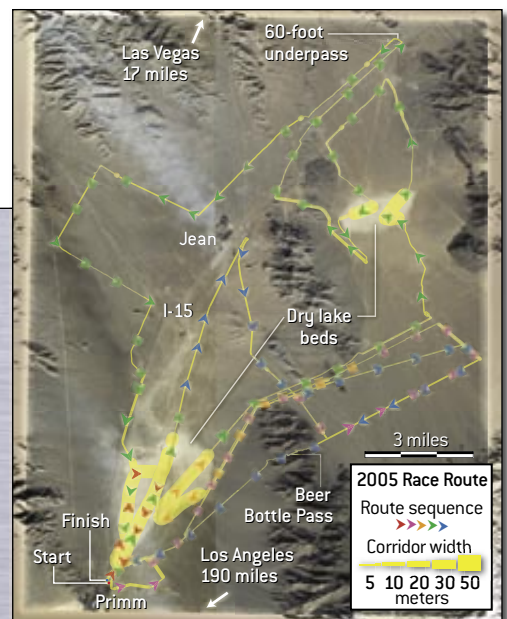
to more than \$100,000 each, the price of long-range laser scanners is formidable. Other kinds of sensors, such as video cameras and radars, can see farther and cost less. Yet these have their own weaknesses, and they produce torrents of data that are infamously hard to interpret.

Many teams equipped their robots with a combination of sensors. But only a few succeeded in building systems that could integrate the disparate perspectives to deduce a safe and fast path ahead—and do so many times a second.

Team Terramax's 15-ton robotic Oshkosh truck completed the course thanks in part to a novel "trinocular" vision system designed by Alberto Broggi's group at the University of Parma in Italy. The program selects from among three pos-

sible pairs of cameras to get an accurate stereo view of the near, medium or distant terrain. The higher its speed, the farther out the robot peers.

After the competition, Thrun reflected that one of the key advantages of his Stanford team's Stanley robot, which won the race and the \$2 million, was its vision-based speed switch. Stanley uses a simple but powerful form of machine learning to hit the gas whenever it spots a smooth road extending into the distance [see box on opposite page].



GRAND CHALLENGE COURSE began and ended in Primm, Nev. Over its 131.7 miles, the route [sequence of colored arrows] included two long underpasses, several railroad crossings and a mountain pass.

And the Winner Is ...

"Last year, the night before the race, I just kept thinking, 'Don't screw up, Sandstorm,'" recalls Chris Urmson, one of the team's technical leaders. "This year, it's more a feeling of anticipation—like Santa Claus is coming."

At 4 A.M. plus 90 seconds, the course comes up on screens in the Red Team's route planning trailer. "Hmm, this is exciting," Alexander Gutierrez says as he scans the convoluted route.

Michael Montemerlo, lead programmer for the Stanford team, is looking at a similar display of the course on his laptop inside Stanley. "What the heck? There's all kinds of overlap—it keeps going in and out. There: there are the mountains, right at the end." Sebastian Thrun, the team leader, looks over his

shoulder. "It's short," Thrun says. "That's sad."

H1ghlander is the first to launch into the rising dawn. If it sticks to its schedule—and in months of desert testing it always has—the vehicle will finish at 1 P.M. after a 6.3-hour run.

Stanley starts five minutes later, followed by Sandstorm and

the remainder of the 23 robots at five- to 10-minute intervals.

By 8:35 A.M. Team DAD's pickup with the spinning laser has passed IVST's truck and is gaining on Sandstorm. An hour later H1ghlander rolls through a 40-mile-an-hour dust storm, having widened its lead on Stanley by seven minutes. Stanley is meanwhile pulling farther ahead of Sandstorm, which the Red Team commanded to drive at a conservative 7.0-hour pace as part of a hare-and-tortoise strategy. Team ENSCO's Dexter, which started in the middle of the pack, is making great time.

As H1ghlander crosses the railroad and hits rolling terrain, it stops midway up a hill and slips back to the bottom, then climbs and falls again. On the third attempt it crests the hill, but clearly the robot's engine is flagging. Stanley catches up, and shortly past noon whoops erupt from the large crowd of Stanford and Volkswagen spectators as Stanley takes the lead.

At 1:51 P.M. Stanley appears at the finish line, soon followed by H1ghlander and Sandstorm. Team Gray's KAT-5 arrives at sunset, as officials pause Terramax, which spends the night idling in the desert and completes its mission the next morning. After checking the robots' time logs, Tether of DARPA pronounces Stanley the Grand Challenge victor, by a margin of 11 minutes.

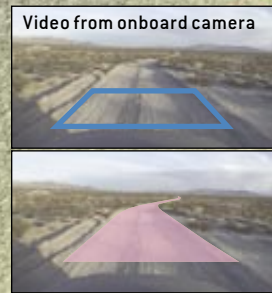


VICTORIOUS Stanley claimed the \$2-million prize for Stanford with an elapsed time of 6.9 hours. Four other robots completed the course: Sandstorm in 7.1 hours, H1ghlander in 7.2, KAT-5 in 7.5, and Terramax in 12.9.

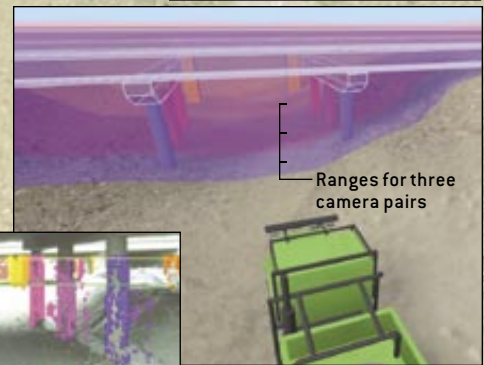
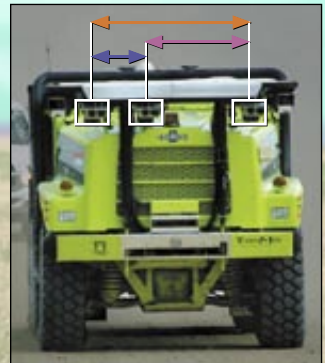
GENE BLEVINS/L.A. Daily News/Corbis (photograph); W. WATT GIBBS (route map) AND IKONOS (satellite image)

VISION LINKED TO SPEED

Smart speed switch, which helped Stanley win the 2005 Grand Challenge, combines laser and video sensors in a four-step process. First, the robot filters its laser data to identify a section of terrain ahead that is smooth and relatively flat (*green*). Second, a program finds the corresponding patch of road in the video frame sent by the onboard camera (*blue outlines*). Next, the system highlights all other areas in the same video frame that match that pattern, which it equates with good, drivable road (*pink areas*). Finally, the software checks whether the matching area completely fills the robot's intended path for the next 130 feet (*orange*). If it does, then the system concludes that a long stretch of open road lies ahead, and it informs the onboard planning computer that it is safe to step on the gas.



Trinocular Terramax (*right*) can build a 3-D stereo view of the world from any of three pairs (*arrows*) of color video cameras. The closest cameras (*purple*), used at slow speeds, can detect obstacles up to 50 feet away. At fast speeds the robot selects its widest pair (*orange*), which can pick up objects 65 to 165 feet ahead. The third pair (*pink*) offers a happy medium.



Terramax might first detect the pillars of an underpass with its long-range stereo cameras (*orange zone above*). As the vehicle slows, it will switch to medium- and then short-range camera pairs to make certain it notices all the obstacles in its video scene (*inset*).

Some of the innovations with the greatest reach, however, appeared on robots that never reached the finish line. The IVST team, for example, devoted desert trials to discovering the optimum sensor configurations for its Desert Tortoise in a variety of “contexts”—such as washboard trail, paved highway or interstate underpass. As the robot drives, explains team leader William Klarquist, “the vehicle chooses an appropriate context that switches off some sensors, switches on others, and reassigns the confidence that it places in each one.” This technique should allow a robot to move from desert to, say, farmland and still perform well by loading a new set of contexts.

In IRV, the Indy Robot Racing Team demonstrated a “plug and play” system for sensors, a feature that is probably a prerequisite for the creation of an autonomous vehicle industry. The far-flung team of more than 100 engineers needed a way to swap sensors and soft-

ware modules in and out of the robot easily as the group tested and refined the system. So they invented a network protocol (analogous to the hypertext transfer protocol on which the Web runs) for autonomous driving.

Each sensor on IRV plugs into a dedicated computer, which boils the raw data down to a set of obstacle coordinates and sizes, and then translates that into the network protocol. Every sensor computer broadcasts its obstacle list to all other sensors and to the robot's central path-planning computer. The standard makes removing a malfunctioning radar or upgrading a buggy vision algorithm as simple as a changing a tire.

With the dust hardly settled from the race, the next milestone for autonomous ground vehicles is not yet clear. DARPA's Tether points to military interest in convoys that use a human lead driver to send coordinates to a pack of robots behind. Whittaker aimed to have H1ghlander tending fences on his farm by the end of 2005, and by November he was already drafting proposals for a lunar mission. Both he and Thrun said they received lucrative offers from commercial investors in the days before the race. So whatever else happens, these robots will keep moving. SA

W. Wayt Gibbs is senior writer.

MORE TO EXPLORE

High Speed Navigation of Unrehearsed Terrain: Red Team Technology for Grand Challenge 2004. Chris Urmson et al. Carnegie Mellon University Technical Report CMU-RI-TR-04-37; June 2004.

Adaptive Road Following Using Self-Supervised Learning and Reverse Optical Flow. David Lieb, Andrew Lookingbill and Sebastian Thrun in *Proceedings of Robotics: Science and Systems I*; June 2005. Available online at roboticsproceedings.org

DARPA Grand Challenge Web sites: www.darpa.mil/grandchallenge and grandchallenge.org

JOHN KOCON (illustrations), SEBASTIAN THRUN Stanford University (video frames); V. ROSS JOHNSON AND SHAHN TORNTOW (photograph, top right); ALBERTO BROGGI University of Parma (inset at bottom right)