

## Feature

# DARPA Grand Challenge – a pioneering event for autonomous robotic ground vehicles

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### Abstract

For the time in its 45-year history, the Defense Advanced Research Projects Agency (DARPA) reached beyond its standard defense contractors and out to the public, and in 2004 held the DARPA Grand Challenge in an effort to attract innovation in order to achieve a military mandate of having one-third of America's ground combat vehicles unmanned by the year 2015. DARPA offered a cash prize of US\$1 million to an autonomous robotic vehicle that could navigate a 142 mile course in the Mojave desert in less than 10 h. Over 100 applications were submitted, and after further evaluations, DARPA narrowed the field to 25 finalists. After qualifying trials, 15 vehicles confronted the starting line on 13 March 2004. Though the farthest a vehicle got was 7.4 miles, the event was viewed as a technological breakthrough. This paper describes the systems that were set-up to monitor and control the event, and features of the various robots.

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## Introduction

For the time in its 45-year history, the Defense Advanced Research Projects Agency (DARPA) reached beyond its standard defense contractors and out to the public, and in 2004, held the DARPA Grand Challenge (DGC) in an effort to attract innovation in order to achieve a military mandate of having one-third of America's ground combat vehicles unmanned by the year 2015.

DARPA offered a cash prize of US\$1 million to an autonomous robotic vehicle that could navigate a 142 mile course in the Mojave desert in less than 10 h. Over 100 applications were submitted, and after further evaluations, DARPA narrowed the field to 25 finalists. After qualifying trials, 15 vehicles confronted the starting line on 13 March 2004.

Although there were no autonomous robotic ground vehicles that could navigate and complete the 142 mile difficult desert course in the Mojave desert, the DGC was considered a technological success.

DARPA was established as an agency of the US Department of Defense (DoD) in 1958 as America's first response to the Soviet launching of Sputnik. DARPA has been the driving force behind technological advancements such as the F-117 stealth fighter, the B-2 bomber, unmanned aircraft such as Global Hawk and the Predator, and perhaps the most famous of all DARPA technology, the Internet, which began in the 1960s with the development of ARPANet and its associated TCP/IP network protocol architecture.

Driven by two recent mandates from the US Congress, one that "it shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that . . . by 2015, one-third of the operational ground combat vehicles are unmanned". And the other providing that DARPA "may carry out a program to award cash prizes in recognition of outstanding achievements in basic, advanced and applied research, technology development, and prototype development that have the potential for application to the performance of the military missions of the Department of Defense". DARPA announced in July 2002, the DGC, a competition to win a million US dollars by traversing approximately 200 miles off- and on-road terrain across California and Nevada in less than 10 h.

Seven months later, in February 2003, nearly 500 prospective participants came to the competitor's conference held in Los Angeles, California. One hundred and six teams submitted applications expressing an interest. Out of the 106 initial group, 86 submitted technical papers by the October 2003 deadline. After a meticulous



evaluation of technical papers and on-site visits to the teams, DARPA selected the final 25 teams; all representing a variety of backgrounds include university researchers, private industry, hobbyists, and even one high school team. A random drawing was determined for the starting order for the teams at the qualification, inspection, and demonstration (QID) event, held on 8–12 March 2004 at the California Speedway near Los Angeles. The teams' starting positions for the Grand Challenge event were based on their performance at the QID (Plate 1).

### Route development

The top priority in route development was to come up with not only a challenging course that was similar to the terrain encountered in warfare, but also that was safe enough to ensure minimal community and environmental impact (Table I). DARPA worked with the appropriate federal, state, and local authorities and underwent rigorous environmental assessment and approval processes with the California and Nevada Bureaus of Land Management.

More than 100 law enforcement officers, security specialists, rangers, biologists, and emergency medical technicians developed a comprehensive safety and environmental protection plan to implement during the Grand Challenge. Assisting with route development was

**Plate 1** Solid terrain modeling provided a 3D model of the 142-mile desert route that started in Barstow, California and ended in Primm, Nevada



**Table I** Course obstacles and terrain types

<b>Natural obstructions</b>	Ridge tops	Paved roads	Cattleguards
<b>Brushland</b>	Rocky trails	Overpasses	Erosion gullies
<b>Dry lakebeds</b>	Sand	Underpasses	Rockfalls
<b>Hard packed trails</b>	Unsurfaced roads	Water	Steep slopes

SCORE International, which has 30 years of experience in planning off-road vehicle events in California and Nevada.

Since the route passed through areas that are the habitat of the desert tortoise, a threatened species as listed by California, Nevada, and the federal government, a team of desert tortoise biologists took special precautions to ensure the tortoises' safety and protection.

### Tracking and control applications

DARPA created an extensive infrastructure to ensure the ability to track and control a wide variety of robots in a remote and challenging environment.

Several purpose-built tracking applications were created that accepted a waypoint file to show route and information about vehicle positions.

Robots, control vehicles, biologists, tow trucks, and other support vehicles were identified by a radio ID. The radio ID mapped to a mnemonic for identification, e.g. B01 for Bot #1, C17 for Control vehicle #17, T54 for Biologist (Turtle person) #54, etc.

Some tracking applications watched near-real time (about a 2 s delay) data streams from vehicles for moment-by-moment updates. Other applications looked at periodic (every 30 s) updates with the most current values for that vehicle.

The primary tracking application, operating in near-real time, provided the same view for the vehicle communicator at the Challenge Operations Center (COC) and the vehicle communicator in the control vehicle. Each robot was followed by its own control vehicle. The robot and control vehicle were electronically paired by a matching set of Omnitech Robotics' E-stop boxes. The box in the bot could only provide a "run" signal when that bot's E-stop box was within range of its paired E-stop controller or one of a half-dozen strategically placed master controllers. The absence of a positive "run" signal (whether because a judge in the control vehicle flipped a switch to "pause" or because of a failure in the control vehicle, robot, or "line of sight" radio link) would be interpreted by the robot as a "pause".

The radio link between the robot and control vehicle provided three functions: run/pause, kill, and global positioning system (GPS) telemetry. GPS telemetry was available locally to the radio operator in the back seat of the control vehicle and was relayed to the DGC local area network (LAN) over Verizon Wireless (terrestrial), Globalstar (satellite), and Iridium (satellite) links.

The Verizon, Globalstar, and Iridium data were received at the network operation center (NOC) in Primm, NV, and broadcast to the DGC LAN segments at the COC also at the finish line in Primm, NV, as well as the situational awareness facility (SAF) at the start line, located 142 miles away in Barstow, CA.

A doublewide trailer served as the COC at the finish line (Plate 2). At one end of the trailer were tables with laptops, and headsets/microphones provided the tracking and communications for interaction with local, federal and state public safety, fire and rescue, Bureau of Land management and biologists.

At the other end of the room, tables along three walls provided a working space for each COC-based vehicle communicator. Each communicator was in constant touch with his or her counterpart in a matching control vehicle. The communicators had use of two land mobile radio (LMR) channels that covered the entire course, cellular telephones, and Globalstar satellite telephones to provide status, update and control information. Four other channels of LMR covered the course for safety, tow trucks, biologists and air operations. In addition to voice communications, the COC-based communicators could see up-to-the-minute tracking information from the GPS-based tracking system.

Because of the overall focus of DARPA to ensure positive control and safety of the robots, the developers were actually freed to focus on the performance characteristics of the robots themselves.

"I've never worked before in an environment (with robots) where safety was not my primary concern" said one member of the Red Team. "Here I could concentrate on performance as my number one design goal, and safety second, since safety was so inherent. It was always the assumption

that if the robot was about to hurt something that the control vehicle would pause or kill it".

"Lots of people can make robots that can travel at a few miles an hour. The really interesting problems happen when the vehicle is traveling fast enough for the inertia of the spinning wheels to be a significant factor in performance, or realizing that steering the vehicle to the left or right may not result in the precise change in direction that is expected because the vehicle is traveling on a less than perfect surface".

GPS information from either the robot or the control vehicle traveled across all available routes. Since the accuracy of the timestamps from each of the GPS positions was assured, the delays in the different paths were not of consequence. For each radio ID, the arrival of each information load at any of the applications was checked to ensure that only the most current packet was processed. Other than for logging purposes, "old" information packets were of no consequences (Plate 3).

The primary tracking application, at maximum magnification, provided a "dot" for the vehicle that was about 10-12 ft in diameter. This dot was an approximation of the average circle of probable error (CPE) for the wide range of GPS equipment in use and the performance of the equipment over a range of operating conditions. The dot was the approximate width of the course at its narrowest, a one-lane jeep trail of about 10-12 ft.

Because of the errors inherent in GPS tracking, a robot that was on the course might appear to the tracking application as being one or two dot diameters off the course to one side or the other. Because the control vehicle had the robot under constant supervision, it was easily possible to determine if, and if so how much, the robot was actually off course.

In the actual competition, the robots were allowed a small amount of latitude to stray off the course as long as they did not endanger people, property, or sensitive habitat areas.

Plate 2 Inside the COC (Photo courtesy of Rupert Scammell)



Plate 3 Internal command and control system (Photo courtesy of Rupert Scammell)



The primary tracking application provided a visual background for the QID track at California Speedway in Fontana, CA and the actual route between the beginning of the route at the Slash X Ranch Bar and Grill near Barstow, CA, and the end of the course; a rear parking lot of Buffalo Bill's Resort and Casino in Primm, NV.

The visual background for the application was the satellite imagery that provided roads, trails, buildings, and relief features. Users of the software could choose to overlay the satellite imagery with a contour interval map of the same area showing political boundaries, power lines, road names, and place names. The user could choose various levels of transparency for the map. By default, the map was invisible (showing only the satellite imagery). At the other extreme, only the map was visible (Plate 4).

The primary tracking application allowed the user to zoom in to see each vehicle icon as 1/4 in. across or zoom out to see the entire 140+ mile course on one PC monitoring screen.

In addition to the map views, the primary tracking application also provided a tabular display showing the vehicles currently being tracked, their location, the time of the latest update and (for the robots) their state (run, pause or disabled).

The start, finish, and the four mountaintop land mobile radio repeater/microwave relay sites all had commercial power and generator back-up.

A LAN connected the COC and the NOC. Wireless LAN connectivity was provided to other points on the resort property at the finish line, including the arena where the primary tracking application was available as one of the video feeds for the gathered staff, volunteers, press, and members of the public.

The LAN was bridged across the microwave point-to-point network to the starting line near Barstow to provide the broadcast packet stream to the situation awareness facility (SAF) at the start line.

During the QID event at Fontana, CA, a commercial Internet connection from the track allowed for the use of point-to-point tunneling protocol (PPTP) from the track to the NOC at

Plate 4 An example of a guidance control system



Primm, NV, to provide network connectivity for tracking information.

Video from the QID event at Fontana was provided to other DGC LAN sites by MPEG streaming video using Vbrick compression hardware and software. The stream was carried over the PPTP connection over the local wireless connections at the Fontana track for QID and the start in Barstow. The local wireless connections terminated at access points that provided connectivity to the DGC extended LAN. Along the course, super control vehicles, equipped to replace a disabled control vehicle, also had the capacity to send video over a 56 kbps Inmarsat satellite phone link (Table II).

## Event results

Although none of the robotic vehicles finished the 140+ mile course, the competitors are listed below in the approximate order of success, from most to least successful. Vehicles that completed the qualification course, or were able to leave the start area at the competition, are listed (Plate 5).

The results of all the competitors, listed in order of team number, can be found in Table III.

Table II Major vendors and technology providers for DARPA's Grand Challenge

Verizon Wireless	www.verizonwireless.com
Globalstar	www.globalstar.com
SRA International	www.sra.com
Cengen	www.cengen.com
3rd Street R & D	http://3rd-st.com
Omnitech Robotics	www.omnitech.com
Inmarsat	www.inmarsat.org
RS Information Systems	www.rsis.com
Solid Terrain Modeling	www.stm-usa.com
Vbrick	www.vbrick.com

Plate 5 Different vehicle types and sizes competed at the DGC



Table III Results of robotic vehicle competitors listed in order of team number

Team no.	Team name	Place	Course distance (miles)	QID attempts	QID completions <sup>a</sup>	Base	Drive <sup>b</sup>	GPS	Lidar	Radar	Inertial guidance	Sonar	Infrared	Vision
01	Team Phantasm	–	c	3	0	Kawasaki ATV	4×4			Yes				
02	CajunBot	–	d	5	0	purpose built atv	6×6		Yes					
03	Team Arctic Tortoise	–	e	e	e	1992 Jeep Cherokee	4×4							
04	Team CIMAR	8	0.5	9	0		Yes							
05	Team Caltech	5	1.3	7	1	1996 Chevrolet Tahoe	4×4	Yes	Yes				Yes	Yes
06	A.I. Motonators	–	f	f	f	Purpose built vehicle off-road		Yes	Yes		Yes			Yes
07	Team DAD	3	6.0	9	3	Toyota pickup	4×4	Yes			Yes			Yes
08	Insight Racing	–	f	f	f	Chevy SUV	4×4				Yes			Yes
09	The Golem Group	4	5.2	3	0				Yes					
10	Palos Verdes High School Road Warriors	–	d	9	0	2003 Honda Acura MDX	4×4		Yes					
11	CyberRider	–	f	f	f	Purpose built vehicle off-road		Yes						
12	Rob Meyer Productions	–	f	f	f			Yes						
13	Team ENSCO	9	0.2	9	0	Purpose built atv	4×4		Yes					
14	Team Spirit of Las Vegas (TSOLV)	–	e	e	e									
15	Team TerraHawk	–	g	3	0	Purpose built			Yes					
16	The Blue Team	–	g	4	0	Motorcycle	2×1	Yes		Yes	Yes			Yes
17	SciAutonics I	7	0.8	6	0	ATV Corp.	4×4	Yes	Yes					
18	Rover Systems	–	g	5	0	Purpose built low profile	4×4			Yes				
19	Team LoGHQ	–	c	1	0	Purpose built vehicle off road								
20	Team TerraMax	6	1.2	7	1	Oshkosh MTVR	6×6	Yes	Yes	Yes		Yes		Yes
21	SciAutonicsII	2	6.7	5	1	Purpose built		Yes	Yes					
22	Red Team	1	7.4	2	2	1986 model 998 HMMWV	4×4	Yes	Yes	Yes	Yes			Yes
23	Axion Racing	–	d	5	1	1994 Jeep Grand	4×4	Yes	Yes	Yes			Yes	Yes
24	Team Overbot	–	e	e	e	Cherokee Limited	6×6		Yes	Yes				Yes
25	Virginia Tech	–	d	5	1	ATV Club car	4×4		Yes	Yes				Yes

Notes: <sup>a</sup>QID completions consisted of completing the obstacle course and sensing the closed gate at the end. <sup>b</sup>A × B indicates: A=number of wheels and B=number of wheels used to propel the vehicle. <sup>c</sup>Did not qualify at QID (did not leave chute and demonstrate ability to be stopped). <sup>d</sup>Did not leave start area, failed to start, or did not maneuver onto first course segment. <sup>e</sup>Withdraw prior to QID. <sup>f</sup>Did not run at qualification, inspection, and demonstration (QID) (Bot never placed in chute). <sup>g</sup>Withdraw prior to start of challenge

## First place

Vehicle 22

### Team name

Red Team (Plate 6)

### Vehicle name

Sandstorm

### Vehicle description

Built on chassis of old Hummer (1986 model 998 HMMWV). Refrigerator-sized box suspended over the center of the passenger compartment with springs and shock absorbers. Controlled environment for computers and electronics. Separate generator for power.

### Organization

Carnegie-Mellon University, Pittsburgh, PA. Thirty five corporate sponsors, published cost estimates of up to US\$3.5 million.

### Results

The vehicle rolled and was seriously damaged in high speed testing on Thursday, 4 March, and qualified on Tuesday, 9 March, after rebuilding the sensor array on the top of the vehicle. Vehicle was the first to qualify during the first full day of qualification. At mile 7.4, on switchbacks in the first mountainous section, the vehicle went-off course and got stuck on a berm. In attempting to extract itself and applying full power to the drive wheels, the spinning front tires caught fire from the friction heating and were extinguished by personnel in the trailing observations/safety vehicle. In the collision with the berm or while trying to extract itself, both front half-shafts (axles) were broken. The vehicle was command-disabled. The loss of GPS precision (as vehicle entered steep terrain, blocking part of the GPS constellation) likely contributed to problems in the mountain

turns. Another problem cited by team members was that the look-ahead effect of examining the waypoints ahead in path planning had the tendency to cut to the inside of curves. While this is normally a desirable behavior, it caused problems on the mountain switchbacks.

### Technologies

Radar; SAIC stereo vision, and scanning laser ranging. Position and orientation are estimated by six-axis inertial sensing and axle encoding; Applanix pose estimator; OmniStar GPS

### References

[www.applanix.com/html/media/med\\_20040305.htm](http://www.applanix.com/html/media/med_20040305.htm); [www.saic.com/](http://www.saic.com/).  
[www.redteamracing.org](http://www.redteamracing.org); [www.ascribe.org/cgi-bin/spew4th.pl?ascribeid=20040315.061553&time=07%2019%20PST&year=2004&public=1](http://www.ascribe.org/cgi-bin/spew4th.pl?ascribeid=20040315.061553&time=07%2019%20PST&year=2004&public=1);  
[www.reviewjournal.com/lvrj\\_home/2004/Mar-14-Sun-2004/news/23432693.html](http://www.reviewjournal.com/lvrj_home/2004/Mar-14-Sun-2004/news/23432693.html)

## Second place

Vehicle 21

### Team name

SciAutonics II (Plate 7)

### Vehicle name

Avidor 2004

### Organization

SciAutonics, LLC and Elbit Systems Ltd.

### Results

At mile 6.7, two-thirds of the way up the first mountain pass, the vehicle went into an embankment and became stuck. The vehicle was command-disabled.

Plate 6 The Red Team prepares their vehicle, Sandstorm



Plate 7 SciAutonicsII receives some last minute preparations (Photo courtesy of Rupert Scammell)

*Technologies*

NavCom Technology's StarFire Network

*References*

www.sciautonics.com; <http://spatialnews.geocomm.com/dailynews/2004/jan/30/news3.html>

**Third place**

Vehicle 7

*Team name*

Digital Auto Drive (D.A.D.)

*Vehicle name*

Team D.A.D. Grand Challenge Vehicle

*Vehicle description*

Toyota 4 × 4 pickup truck.

*Organization*

Digital Auto Drive

*Results*

The vehicle paused at mile 6.0 to allow a wrecker to pass on the narrow course. The vehicle got hung on a rock and was unable to proceed forward. The vehicle was command-disabled.

*Technologies*

Visual imaging: real time imaging (RTI) system used state-of-the art TI DSP 64 × × DSP chips running at over 1 GHz and two Panasonic CCD production-quality camera units, with customized control boards. GPS: Navcom 2050G GPS unit. Inertial measurement: Analog Devices ADXL-203 accelerometers

*References*

[www.digitalautodrive.com](http://www.digitalautodrive.com)

**Fourth place**

Vehicle 9

*Team name*

The Golem Group

*Vehicle name*

Golem I

*Results*

At mile 5.2, while going up a steep hill, the vehicle developed a throttle problem that kept it from proceeding further. It stopped on the road, in gear, and tried for an hour to continue. The vehicle was command-disabled.

*References*

[www.miami.com/mld/miamiherald/business/national/8193962.htm](http://www.miami.com/mld/miamiherald/business/national/8193962.htm)

**Fifth place**

Vehicle 5

*Team name*

Team Caltech

*Vehicle name*

Bob (Plate 8)

*Vehicle description*

1996 Chevrolet Tahoe 4 × 4

*Organization*

California Institute of Technology

*Total distance*

1.3 miles

*Results*

The vehicle veered off course, went through a fence, and tried to return to the road. It could not get through the fence again. The vehicle was command-disabled.

*Technologies*

Stereo cameras; Infrared sensors; Lasers; NavCom Technology's StarFire Network

*References*

<http://spatialnews.geocomm.com/dailynews/2004/jan/30/news3.html>; [www.team.caltech.edu](http://www.team.caltech.edu)

**Sixth place**

Vehicle 20

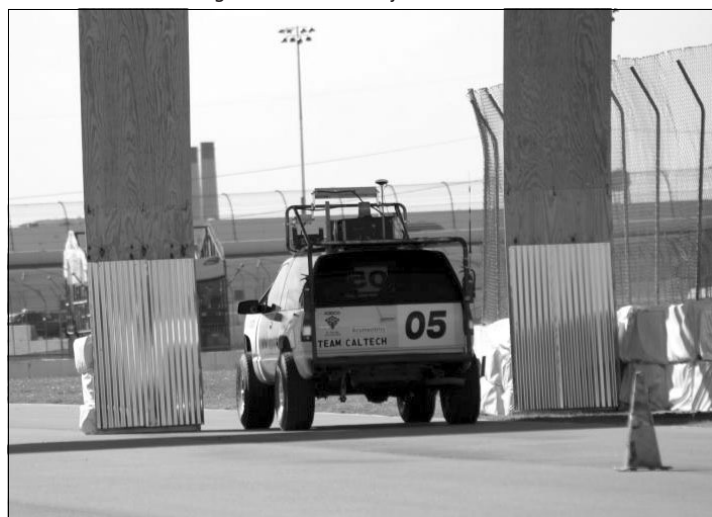
*Team name*

Team TerraMax

*Vehicle name*

TerraMax

Plate 8 Vehicle BOB negotiates one of many obstacles on the course



*Vehicle description*

Production model US Marine Medium Tactical Vehicle Replacement (MTVR)

*Organization*

Oshkosh Truck Corporation

*Results*

At 1.2 miles, the vehicle appeared to be confused by bushes (tumbleweeds) near the course. Vehicle was command-disabled

*Technologies*

GPS; Ladar; Radar; Sonar; Vision

*References*

[www.eleceng.ohio-state.edu/terramax/](http://www.eleceng.ohio-state.edu/terramax/);  
[www.argo.ce.unipr.it](http://www.argo.ce.unipr.it); [www.oshkoshtruck.co.uk/Products/MTVR.cfm](http://www.oshkoshtruck.co.uk/Products/MTVR.cfm); [www.scienceblog.com/community/article2292.html](http://www.scienceblog.com/community/article2292.html)

**Seventh place**

Vehicle 25

*Team name*

Virginia Tech

*Vehicle name*

Cliff

*Organization*

Virginia Tech

*Results*

The vehicle finished the qualification course, but its brakes locked up in the start area at the competition. The vehicle was removed from the course.

*References*

[www.me.vt.edu/grandchallenge/](http://www.me.vt.edu/grandchallenge/)

**Eighth place**

Vehicle 23

*Team name*

Axion Racing

*Vehicle name*

Spirit of Kosrae

*Vehicle description*

1994 Jeep Grand Cherokee Limited

*Organization*

Axion, LLC

*Results*

The vehicle finished the qualification course, but it circled the wrong way in the start area of the competition. The vehicle was removed from the course.

*Technologies*

GPS; FLIR; LADAR; RADAR; Stereo vision cameras

*References*

[www.axionracing.com](http://www.axionracing.com)

**Ninth place**

Vehicle 17

*Team name*

SciAutonics I

*Vehicle name*

RASCAL

*Organization*

SciAutonics, LLC

*Results*

The vehicle did not successfully complete the qualification course. The vehicle went off the route after 0.75 miles. It tried unsuccessfully for 90 min to reacquire the route, without any movement, and then the vehicle was command-disabled.

*Technologies*

NavCom Technology's StarFire Network

*References*

[www.sciautonics.com](http://www.sciautonics.com); <http://spatialnews.geocomm.com/dailynews/2004/jan/30/news3.html>

**Tenth place**

Vehicle 4

*Team name*

Team CIMAR

*Vehicle name*

NaviGATOR

*Organization*

University of Florida, Center for Machine Intelligence and Robotics and Autonomous Solutions, Inc.

*Results*

At the 0.5 mile mark, the vehicle ran into an old fence beyond the limits of the course and became entangled. The vehicle was command-disabled and removed from course.

*Technologies*

NavCom Technology's StarFire Network

*References*

<http://spatialnews.geocomm.com/dailynews/2004/jan/30/news3.html>; [http://cimar.mae.ufl.edu/grand\\_challenge/](http://cimar.mae.ufl.edu/grand_challenge/);

[www.autonomoussolutions.com/](http://www.autonomoussolutions.com/); <http://cimarmae.ufl.edu/CIMAR/>

### **Eleventh place**

Vehicle 13

#### *Team name*

Team ENSCO

#### *Vehicle name*

DAVID

#### *Vehicle description*

4 wheel ATV

#### *Organization*

ENSCO, Inc.

#### *Results*

The vehicle did not complete qualification. At mile 0.2 (within sight of the starting line), the vehicle overcorrected for off-track behavior, drove onto a raised berm and rolled. The vehicle was removed from the course.

#### *Technologies*

NavCom Technology's StarFire Network

#### *References*

[www.ensco.com](http://www.ensco.com)

### **Conclusion**

Though none of the 15 DARPA approved robot vehicles completed the 142 mile course in the Mojave desert to claim the US\$1 million prize, the US DOD agency felt that the development of autonomous robotic vehicle technologies was very valuable for America's defense on the battlefield and plans to harvest the technologies demonstrated.

DARPA also plans to hold another grand challenge in 2005. The prize is US\$2 million for an autonomous robotic vehicle that can complete the new course.

Additional information on the DGC can be found at the Web site: [www.darpa.mil/grandchallenge/](http://www.darpa.mil/grandchallenge/).