Grand Challenge 2004

Final Report

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I. Background

Section 2374a of Title 10 of the United States Code authorizes the Secretary of Defense, acting through the Director of the Defense Advanced Research Projects Agency (DARPA), to award prizes in amounts up to $10 million to recognize 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 (DoD). The Annual report requirements are:

> **Annual report.**--Promptly after the end of each fiscal year during which one or more prizes are awarded under the program under subsection (a), the Secretary shall submit to the Committees on Armed Services of the Senate and the House of Representatives a report on the administration of the program for that fiscal year. The report shall include the following:
>
> (1) The military applications of the research, technology, or prototypes for which prizes were awarded.
>
> (2) The total amount of the prizes awarded.
>
> (3) The methods used for solicitation and evaluation of submissions, together with an assessment of the effectiveness of those methods.

There were no prizes awarded and, therefore, an official report is not required.

On the other hand, an event was held on March 13, 2004, and another event is scheduled to be held on October 8, 2005.

The first event was a success even though an award was not made. DARPA believed the experiences and details should be shared with those who made this possible. Therefore, DARPA is providing the Congress with a status report providing all information requested in the Act as if a prize award had been made.

Rationale for Using Congressional Prize Authority for Autonomous Ground Vehicle Development

Following a series of studies, and influenced by a Congressional directive[1], DARPA determined that the first use of the Congressional prize authority would be in the area of autonomous ground vehicles with the following goals:

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[1] Congress expressed a clear interest in accelerating unmanned vehicle capabilities and, in fact, set a goal for the Department of Defense: The Fiscal Year 2001 National Defense Authorization Act states, "It shall be the 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 of the Armed Forces are unmanned." Given the aggressive timeline in the directive, DARPA determined that organizing a prize authority event would be the quickest and most cost-effective approach to stimulate innovation and expand the research community in autonomous ground vehicle technologies.

- Increase the number of performers working on autonomous ground vehicle technologies.

- Provide DoD access to new talent, new ideas, and innovative technologies by motivating and enlisting innovators that would not normally work on a DoD problem.

- Accelerate autonomous ground vehicle technology development in the United States in the areas of sensors, navigation, control algorithms, vehicle systems, and systems integration.

While there have been a number of significant technical breakthroughs leading to robust unmanned air vehicles that U.S. forces use today, progress in unmanned, autonomous ground vehicle technology has not occurred at a similar rate. Vehicle operations in a ground environment are a much more difficult challenge due to terrain, manmade obstacles, and weather.

A survey of the current state of the research shows a relatively small number of research groups tackling some very hard problems that must be solved to enable military vehicles to traverse difficult terrain. The research emphasis has been on fundamental understanding, and the approaches are often very computationally intensive. As a result, prototype vehicles often operate at very slow speeds (Figure 1; lower left side). Work in this area continues to address increasingly difficult route planning and terrain navigation challenges, but under the assumption Moore's law would enable higher vehicle speeds in the future.

DoD missions require autonomous ground vehicles that not only have sensors and navigation capabilities for operations on varied terrain and with varying amounts of autonomy, but they must also be able to operate at militarily relevant speeds, defined as an average minimum speed of approximately 15-20 mph over some relevant distance.

DARPA established the Grand Challenge to hasten innovation in the area of an unmanned autonomous vehicle that could travel at tactically relevant speeds over distance. Using the prize authority, DARPA would award $1 million to the first team that demonstrated a fully autonomous, unmanned ground vehicle capable of traveling a militarily relevant distance and speed across terrain similar to that encountered by U.S. forces in overseas operations. The winning vehicle would be one that traveled 142 miles across desert terrain in the best time under 10 hours.

Through the Grand Challenge, DARPA has attracted a new, larger set of performers focused on meeting the DoD needs of autonomous vehicles that can travel at realistic speeds. Recasting the autonomous vehicle navigation problem in this way has sparked interest new technologies and kicked off a new generation of efforts focused on practical shorter term goals.

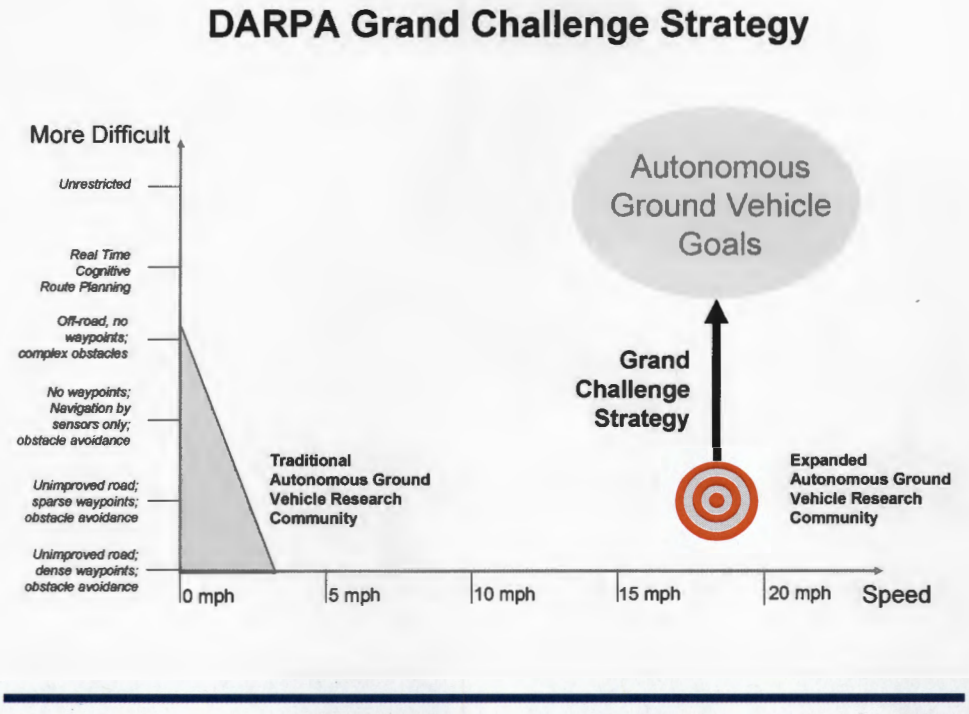

Figure 1. Grand Challenge Strategy

II. Methods Used for Solicitation and Evaluation of Submissions

Solicitation and evaluation methods for the Grand Challenge included the DARPA web site; competitors' conference; entrant technical paper submissions; and a qualification, evaluation, and demonstration event.

A. DARPA Web Site

DARPA developed a website devoted to providing information about the Grand Challenge, including an explanation of the application process. Interested participants and entrants used the website to communicate directly with DARPA. The website contained a discussion forum that participants used to share ideas about technical approaches for autonomous ground vehicles, including obstacle detection, navigation and position location, sensing, control software, and vehicle components. Participants also used the forum to share ideas on how to obtain sponsors and to locate experts in specific technical areas.

B. Competitors' Conference

DARPA held a competitors' conference on February 22, 2003, in Los Angeles, California, as the official start of the Grand Challenge. Conference goals were to provide information about the upcoming event to potential participants, sponsors, and the media; provide a forum in which interested individuals, teams, and sponsors could meet to exchange ideas and set up partnerships leading to eventual entry in the event; and give DARPA a sense of the number of participants interested in competing in the Grand Challenge. The conference attracted over 400 attendees.

C. Team Selection and Review Process

DARPA determined that it would be necessary to limit to 20 the number of vehicles that could compete in the Grand Challenge event on March 13, 2004. The 20-vehicle limit ensured that competing vehicles could safely start and finish the Grand Challenge route within 1 day's daylight hours and within the 10-hour goal. Options to host the event over several days were rejected because of cost.

Since a primary Grand Challenge goal was to provide DoD access to new talent, new ideas, and innovative technologies, DARPA instituted entrant eligibility and funding restrictions, including:

- Prohibition of U.S. Federal Government organizations to lead or participate as a member of a team;
- Requirement that Federal employees could participate on a team only as private citizens on their own time;
- Prohibition on the use of Federal funding by teams or sponsors to prepare for or participate in the Grand Challenge; and
- Prohibition on the use of Government-owned equipment in preparation for or during the Grand Challenge, except equipment and supplies offered to all teams.

Eligible entrants submitted an application followed by a detailed technical paper on their proposed vehicle to qualify and participate in the Grand Challenge. DARPA received 106 applications from potential teams. Eighty-six teams subsequently submitted technical papers by the required deadline. Each technical paper contained specifics on system description (e.g., mobility, power, sensors, and communications), system performance, and safety and environmental impacts (e.g., speed and radiators).

DARPA evaluated each paper to assess whether the entrant's vehicle complied with the requirements specified in the rules. The papers were the basis for the technical inspection at the Qualification, Inspection, and Demonstration (QID) event. The papers also provided insights on the state of autonomous ground vehicle research in the community. DARPA published the technical papers as part of the Grand Challenge proceedings.

Of the 86 technical papers reviewed, 45 teams proposed autonomous vehicle ideas that would be of interest to DoD and, therefore, could compete in the Grand Challenge. However, not all teams appeared they would have vehicles ready in time to compete in the March 2004 event. Of those 45 teams, DARPA selected 19 teams for advancement to the next phase of the Grand Challenge and established a site visit process to determine the final 6 teams.

On December 19, 2003, DARPA announced that 25 teams from around the United States (Figure 2) had been selected to participate in the next stage—qualification, inspection, and demonstration—of the DARPA Grand Challenge.

Figure 2. Initial Group of DARPA Grand Challenge 2004 Selectees – a Diverse Collection of Entrepreneurs, Inventors, and Visionaries

D. Qualification, Inspection, and Demonstration (QID)

The QID was used to determine the final 20 participants for the Grand Challenge. The 25 teams that passed the technical paper review process were invited (21 actually participated) to the QID at the California Speedway in Fontana, California, March 8–12, 2004 (Figure 3). The QID comprised several distinct activities: a static, safety, and technical inspection of the robotic vehicles and their systems; a separate practice area; and a demonstration course of approximately 1.4 miles that the vehicles were required to traverse.

The technical inspection ensured that each vehicle complied with all rules and was safe to operate. The demonstration course ensured that each vehicle could demonstrate intelligent autonomous sensing and navigational capabilities around a series of static and movable obstacles designed to represent those that might be found on the actual course (see Figure 4). The course also provided an opportunity to test the electronic-stop (E-stop) systems of each vehicle and other equipment and procedures that would be used during the actual event.

Each vehicle was ranked according to its overall time to complete the course, and point deductions were taken for impacting obstacles, exceeding established speed limits, or deviating from the established course. Over the 5-day period, eight teams completely finished the course, nine teams partially finished the course, two teams terminated within the starting area, and two teams officially withdrew from the event. On March 12, 2004, DARPA announced that 15 of the 21 teams at the QID qualified for the Grand Challenge event.

Figure 3. The California Speedway Provided the Necessary Facilities for the QID March 8-12, 2004

Figure 4. QID Included Obstacle and Representative Terrain Features

The selected teams (in official starting order) were:

1. Red Team – Pittsburgh, Pennsylvania
2. SciAutonics II – Thousand Oaks, California
3. Team CalTech – Pasadena, California
4. Digital Auto Drive (D.A.D.) – Morgan Hill, California
5. Virginia Tech – Blacksburg, Virginia
6. Axion Racing – Westlake Village, California
7. Team Cajunbot – Lafayette, Louisiana
8. Team ENSCO – Falls Church, Virginia
9. Team CIMAR – Gainesville, Florida, and Logan, Utah
10. Palos Verdes High School Road Warriors – Palos Verdes Estates, California
11. SciAutonics I – Thousand Oaks, California
12. Team TerraMax – Oshkosh, Wisconsin
13. Team TerraHawk – Gardena, California
14. The Golem Group – Santa Monica, California
15. The Blue Team – Berkeley, California

E. The DARPA Grand Challenge

Route Selection

In early 2003, DARPA identified potential locations and routes on which to conduct the Grand Challenge. The Mojave Desert was selected as the general location because its overall terrain characteristics best correspond to the type of operating environments U.S. military forces encounter in the Middle East. Initial plans had the course starting in Los Angeles, California, and finishing in Las Vegas, Nevada. Due to logistical and other planning constraints, the Grand Challenge venues for the QID and the start and finish lines were at separate locations.

DARPA conducted several route surveys to select the primary and alternate routes for the Grand Challenge course. These surveys considered overall terrain navigability, environmental restrictions, and course manageability. The selected option was a 142-mile course beginning in Barstow, California; ending in Primm, Nevada (Figure 5); and traversing a large portion of the Mojave Desert in California and Nevada.

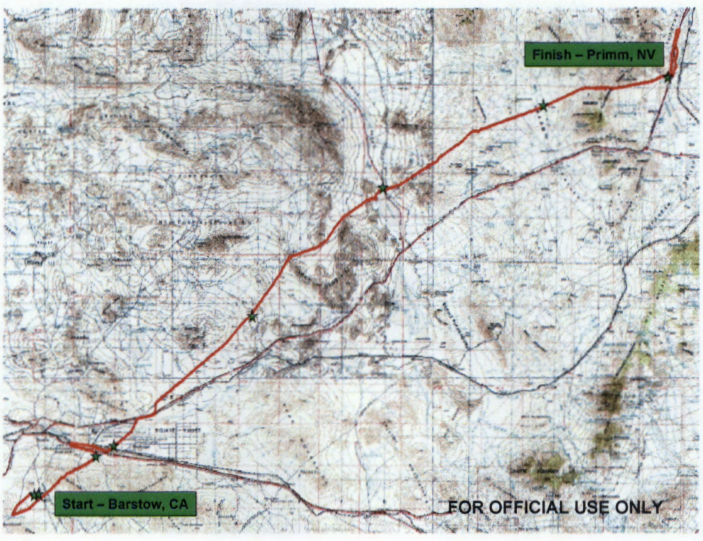

Figure 5. Route of DARPA Grand Challenge 2004

Grand Challenge

At 6:30 AM on Saturday, March 13, 2004, "Sandstorm," the Red Team autonomous robotic ground vehicle sped from the starting chute at the Slash X Ranch in Barstow, California, marking the start of the DARPA Grand Challenge (Figure 6). Over the next 2 hours, each autonomous ground vehicle and its accompanying DARPA control vehicle began the 142-mile journey toward the finish line in Primm, Nevada (Figure 7).

No vehicle was able to complete the 142-mile Grand Challenge course.

Figure 6. Start of Grand Challenge 2004

Figure 7. SciAutonics on the Route

The official results of DARPA Grand Challenge 2004 are:

- Vehicle 22 - Red Team – At mile 7.4, on the switchbacks in a mountainous section, the vehicle veered off course, got caught on a berm, and could not overcome the obstacle.
- Vehicle 21 – SciAutonics II – At mile 6.7, two-thirds up Daggett Ridge, the vehicle went into an embankment and became stuck.
- Vehicle 7 - Digital Auto Drive – At mile 6.0, the vehicle was paused to allow a wrecker to pass through, but upon resuming motion, the vehicle was stuck by a football-sized rock.
- Vehicle 9 - Golem Group – At mile 5.2, while going up a steep hill, the vehicle stopped on the road, in gear and with engine running, but without enough throttle to climb the hill.
- Vehicle 5 - Team Caltech – At mile 1.3, the vehicle veered off course, went through a fence, tried to come back on the road, but could not get through the fence again.
- Vehicle 20 - Team TerraMax – Several times, the vehicle sensed bushes near the road, backed up, and corrected itself. At mile 1.2, it was unable to proceed further.
- Vehicle 17 - SciAutonics I – At mile 0.75, the vehicle went off the route. For 90 minutes, sensors attempted unsuccessfully to regain the route, but without any movement.
- Vehicle 4 - Team CIMAR – At mile 0.45, the vehicle ran into some wire and got completely tangled in it.
- Vehicle 13 - Team ENSCO – The vehicle began smoothly, but at mile 0.2, when making its first 90-degree turn, the vehicle flipped. The vehicle was removed from the course.
- Vehicle 25 - Virginia Tech – The vehicle brakes locked up in the start area; the vehicle was removed from the course.
- Vehicle 23 - Axion Racing – The vehicle circled the wrong way in the start area; it was removed from the course.
- Vehicle 2 - Team CajunBot – The vehicle brushed a wall on its way out the chute; the vehicle was removed from the course.

- Vehicle 10 - Palos Verdes High School Road Warriors – The vehicle hit a wall in the start area; it was removed from the course.
- Vehicle 15 - Team TerraHawk – Withdrew prior to start.
- Vehicle 16 - The Blue Team – Withdrew prior to start.

III. Prize

No prize was awarded since no vehicle completed the 142 mile course in less than 10 hours.

IV. Grand Challenge Methods Effectiveness

Although no autonomous vehicle completed the DARPA Grand Challenge 2004 course, DARPA achieved the stated goals for the prize authority event:

- Goal: Increase the number of performers working on autonomous ground vehicle technologies.

- Goal: Provide DoD access to new talent, new ideas, and innovative technologies by motivating and enlisting innovators that would not normally work on a DoD problem.

  Effectiveness: There was significant publicity as a result of the event, which increased the public's awareness about the DoD desire to develop autonomous ground vehicles. More than 330 credentialed media representatives from the United States and other nations attended the QID and Grand Challenge events March 8–13, 2004. As of March 16, 2004 (for the U.S. only), this media coverage had resulted in more than 450 television news segments, including pieces on ABC *World News Tonight*, NBC *Nightly News*, and CNN; 9 stories on radio stations such as National Public Radio and Canadian Broadcasting; 58 articles in newspapers such as *USA Today*, *The New York Times*, and *The Washington Post*; and coverage on websites such as The Drudge Report, WiredNews.com, and CNET.com. During the period March 10–17, 2004—which included portions of the QID in Fontana, California, and the entire Grand Challenge itself—the DARPA websites received more than 45 million hits from approximately 140 countries around the world. This intense media interest substantially increased interest in robotic technologies and in the Grand Challenge.

Many of the 400 attendees at the competitors' conference and many members of the 86 teams that submitted technical papers had not previously worked on autonomous ground vehicle technology, and many had not worked on a DoD project before the Grand Challenge.

There is credible evidence that the number of individuals interested in working on autonomous ground vehicle technology is growing. In the 3 weeks immediately following the March 2004 Grand Challenge event, DARPA received more than 200 e-mail messages from interested individuals seeking information and declaring interest in participating in the next Grand Challenge. The inquiries were from U.S. corporations, educational institutions, universities, and high schools. The e-mail messages were sent prior to an official public announcement from DARPA regarding the date, location, or conditions of the second Grand Challenge. Since the announcement, the DARPA Grand Challenge website has experienced approximately 15,000 hits per month.

- Goal: Accelerate autonomous ground vehicle technology development in the United States in the areas of sensors, navigation, control algorithms, vehicle systems, and systems integration.

  DARPA used experts in the fields of robotics and sensing technology to evaluate the technologies utilized by the teams seeking to participate in the Grand Challenge and to recognize relevant technological highlights and innovative ideas of potential interest to DoD. The independent technical evaluation team identified the following technology from Grand Challenge 2004 noteworthy:

  - Shock isolation system for autonomous sensors and electronics
  - Custom hardware solution for low-cost, real-time stereo algorithm with reflexive planning
  - Active/Passive trailing arm suspension with articulated centers
  - Dynamically balancing motorcycles
  - Optical flow for berm/ditch detection (conceptual)
  - Multiterabyte terrain data collection and planning
  - Terrain-matching technique (conceptual, proprietary)
  - Route recording and route playback techniques with 3-D model gap filling
  - Sensor-based slippage detection (conceptual)
  - Drive-by-wire as an enabling technology
  - Rotating ladar for foveal sensing
  - Computationally efficient path planning algorithm
  - Multi-strategy (20) backing maneuvers for a large, nonholonomic vehicle
  - Dual global positioning system (GPS) antennas
  - Extended range of low-cost, ultrasonic sensors
  - Adaptive sensor pointing and stabilization

- Single-point laser rangefinder as a low-cost distance sensor
- Smooth GPS waypoint following achieved through nonobvious design of a low-level control algorithm
- LabView (commercial, off the shelf) software development environment and robot controller
- Environmentally conscious design

V. Grand Challenge 2005

DARPA believes it prudent to continue with the prize authority approach and hold a second Grand Challenge for autonomous unmanned ground vehicles in 2005. The prize authority approach is meeting the goals of attracting new talent with new ideas and accelerating advancement in robotic vehicle research. Without the Grand Challenge, it is doubtful there would be much progress without substantial new investment in accelerating research on autonomous ground vehicles that could traverse difficult terrain at militarily relevant speeds.

Many teams that competed in Grand Challenge 2004 continue work on their innovative technologies and plan to compete again. There is also a substantial amount of new interest as evidenced by the significant number of inquiries DARPA receives daily.

On June 8, 2004, DARPA announced the next Grand Challenge will be held October 8, 2005, in the California/Nevada area with an increase in the prize to $2 million. Approval to increase the prize was approved by the Acting Under Secretary of Defense (Acquisition, Technology and Logistics) on April 26, 2004.

DARPA will begin the process with a competitors' conference in August 2004 and will use video submissions and site visits to evaluate each team's eligibility. DARPA will invite 40 eligible teams to a national qualification event, from which 20 teams will be selected to compete on October 8, 2005, on a route similar in distance and terrain to the 2004 event.