REPORT TO CONGRESS

DARPA Prize Authority

Fiscal Year 2005 report in accordance with 10 U.S.C. § 2374a

Defense Advanced Research Projects Agency

MARCH 2006

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APPENDICES

1 REQUIREMENT

This report fulfills the reporting requirements of Section 2374a of Title 10 of the United States Code (Appendix A), which authorizes the Secretary of Defense, acting through the Director of the Defense Advanced Research Projects Agency (DARPA), to award up to $10 million in cash prizes to recognize outstanding achievements in basic, advanced, and applied research; technology development; and prototype developments that have the potential for application to the performance of the military missions of the Department of Defense (DoD).

Section 2374a was amended by Section 257 of the National Defense Authorization Act for Fiscal Year 2006 (Appendix B). This report contains the additional information requested by the amendment.

During the period April 2004 to October 2005, DARPA Grand Challenge 2005 was planned and executed, and a $2 million prize was awarded on October 9, 2005.

2 BACKGROUND

In 2003, after review of the National Academy of Engineering* report on prize competitions and consultation with military leaders, DARPA determined the prize authority granted by Congress should be used to accelerate the development of autonomous ground vehicles. This decision supported the Congressional mandate stated in the Fiscal Year 2001 National Defense Authorization Act that "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 are unmanned."

The first DARPA Grand Challenge offered a $1 million prize for the fastest autonomous vehicle to complete a difficult course through the desert in less than 10 hours. On March 13, 2004, 15 robotic vehicles attempted the route through the Mojave Desert in pursuit of this goal. The most successful vehicle completed approximately 7 miles of the 142-mile route.

Although no vehicle completed the course or even got very far, the first Grand Challenge is considered a success by many for the interest and spirit the event created—best summarized in the announcement of the 2004 Scientific American 50 Awards:

> Of the 15 vehicles that started the Grand Challenge . . . not one completed the 227 kilometer course. One crashed into a fence, another went into reverse after encountering some sagebrush, and some moved not an inch. The best performer, the Carnegie Mellon entry, got 12 kilometers before taking a hairpin turn a little too fast. The $1-million prize went unclaimed. In short, the race was a resounding success. The task that the Pentagon's most forward-thinking research branch . . . set out was breathtakingly demanding. Most bots can barely get across

* National Academy of Engineering, *Concerning Federally Sponsored Inducement Prizes in Engineering and Science*, 1999.

> a lab floor, but DARPA wanted them to navigate an off-road trail at high speed with complete autonomy. The agency had expected maybe half a dozen teams, but more than 100, ranging from high school students to veteran roboticists, gave it a try. The race . . . concentrated the minds of researchers, blown open the technological envelope and trained a whole generation of roboticists.[†]

The Under Secretary Defense (Acquisition, Technology and Logistics) determined the Grand Challenge showed great promise and authorized the prize to be increased to $2 million. On October 8, 2005, the second Grand Challenge was held with a $2 million prize for the fastest vehicle capable of traversing a difficult 132-mile course through the desert in less than 10 hours.

3 CONSULTATION

In planning Grand Challenge 2005, DARPA senior staff consulted with senior civilian and military leaders, including:

- Under Secretary of Defense for Acquisition, Technology and Logistics
- Director, Defense Research and Engineering
- Commandant, U.S. Marine Corps
- Commanding General, U.S. Army Training and Doctrine Command

The Grand Challenge goals and the progress toward achieving those goals were discussed in the context of military autonomous vehicle requirements. These discussions concluded that Grand Challenge 2004 had set the stage for rapid progress in achieving DoD goals. Developing a strong robotics technology base in the United States was unanimously regarded as an area of strategic importance to DoD.

In addition, the prize authority enables DARPA to reach beyond the ranks of the existing autonomous vehicle research community and energize a new generation of scientists and engineers working in the field of autonomous ground systems. The competitive format enables the direct evaluation and comparison of a large number of competing technologies and provides valuable insight to technology planners and decision-makers.

As part of this process, DARPA received authorization from the Under Secretary of Defense for Acquisition, Technology and Logistics to offer a $2 million prize for Grand Challenge 2005.

[†] "The 2004 Scientific American 50 Award," *Scientific American*, December 2004, p 65.

4 GOALS

Autonomous ground vehicles operate in complex, dynamic environments that require layered, context-driven reasoning and sophisticated control strategies. When real-world factors such as inclement weather, difficult terrain, or limited visibility due to dust or nightfall are introduced, the problem of vehicle control at military-relevant speeds can quickly become intractable. While research on individual components or algorithms to address these challenges is valuable, the competition format of the Grand Challenge emphasizes full-system integration and reliable performance at realistic speeds (15-20 mph). Full-system solutions require design trade-offs and integrated solutions, with an emphasis on practicality and cost-effectiveness. Recasting the autonomous vehicle navigation problem in this way has sparked interest in new technologies and kicked off a new generation of innovative approaches.

Specifically, Grand Challenge 2005 goals were to:

- Accelerate autonomous ground vehicle technology development in the areas of sensors, navigation, control algorithms, hardware systems, and systems integration. These areas are important to autonomous ground vehicle operations.
- Demonstrate an autonomous vehicle able to travel over rugged terrain at militarily relevant speeds and distances. A successful technology demonstration could shift perceptions within the technical and operational communities.
- Attract and energize a wide community of participants not previously associated with DoD programs or projects to bring fresh insights to the autonomous vehicle problem.

5 METHODS

Rules. The Grand Challenge rules covered team qualification, funding, vehicle qualification, and event operations. While on the course, vehicles were required to operate entirely autonomously, as stated in Section 3.2 of the Grand Challenge 2005 rules:

> Participating vehicles must demonstrate fully autonomous behavior and operation at all times during the NQE and Grand Challenge Event. Vehicles must be unmanned, and no animals are permitted onboard.
>
> The entry must be a ground vehicle that is propelled and steered principally by traction with the ground. The type of ground contact devices (such as tires, treads, and legs) is not restricted. The vehicle must not damage the environment or infrastructure at the National Qualification Event (NQE) or along the Grand Challenge route. Vehicle operation must conform to any regulations or restrictions imposed by the applicable land-use authority.
>
> The vehicle must be able to pass through any underpasses encountered on the route. The clear opening of the smallest underpass will measure no less than 10 feet in width and 9 feet in height. Maximum vehicle weight is 20 tons; any

team whose vehicle weighs more than 10 tons must provide its own off-road recovery capability. The vehicle must be able to travel on asphalt pavement without damaging the pavement surface.

In addition, vehicles were required to detect and avoid obstacles along the route, posing a considerable technical challenge. The complete set of rules is available at http://www.darpa.mil/grandchallenge05.

During the competition, detailed operational instructions via web mail and web site postings were provided for each phase of the competition.

Application Process. The event was officially announced on June 8, 2004, in a press release widely reported in the media and on the Internet. Information was distributed using an extensive e-mail list and a web site linked to the heavily-visited DARPA home page to ensure all interested parties were afforded an opportunity to participate.

The Grand Challenge required team leaders be U.S. citizens. Teams were allowed to use Government-funded resources such as software libraries, global positioning system (GPS) signals, or test ranges to develop their autonomous vehicles, but only if the resources were uniformly available to all teams; teams were not allowed to charge expenses to a Government contract. Teams certified adherence to these restrictions as part of the application process.

The Grand Challenge Participants Conference was held on August 14, 2004, in Anaheim, California, to allow potential entrants to meet directly with DARPA representatives and discuss all aspects of the event. Suggestions and comments to a set of draft rules that were issued weeks before the conference were discussed with conference attendees to ensure consistency and clarity. A networking session at the conference was held to enable team-formation and information-sharing among attendees.

By the application deadline (February 11, 2005), DARPA received 195 applications, from 36 states (see Figure 1) and 3 foreign countries (New Zealand, Canada and France)—an 84 percent increase over the 106 applications received for the 2004 event.

The practicalities of race operations as well as the Bureau of Land Management event permit limited the number of autonomous vehicles allowed on the Grand Challenge route to 25. As a result, DARPA developed a qualification and selection process that consisted of three stages: evaluation of a team video showing the vehicle in operation; evaluation of each autonomous vehicle by DARPA staff during a site visit; and evaluation at the National Qualification Event (NQE), held for 8 days immediately preceding the Grand Challenge Event (GCE).

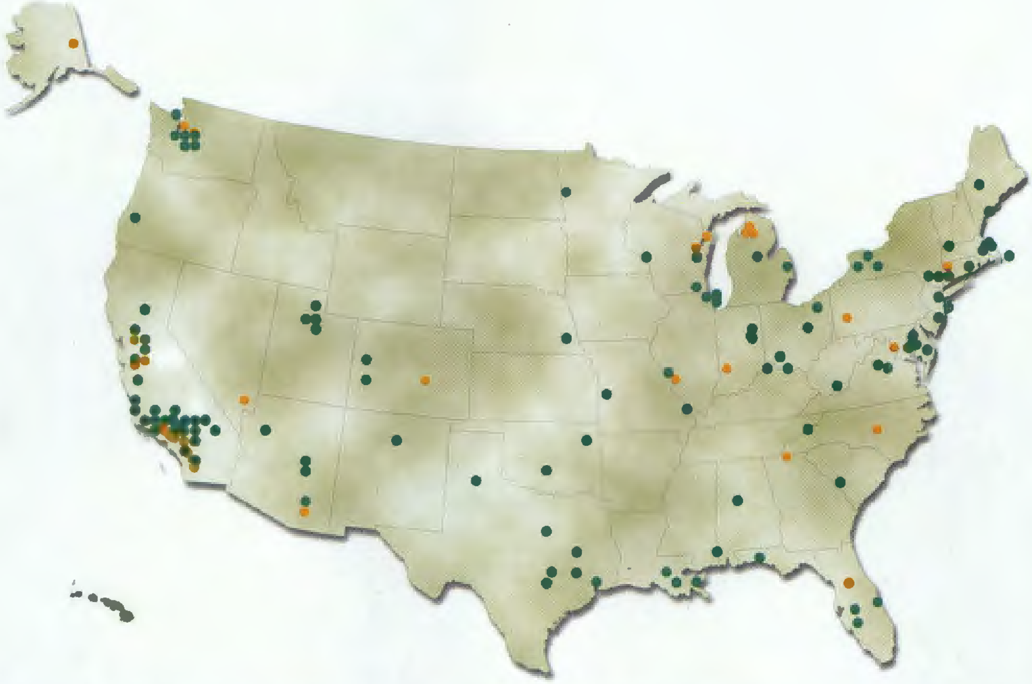

Figure 1. Thirty-five returning teams (orange dots) and 160 new teams (green dots) applied to Grand Challenge 2005.

Video Demonstration. To aid in preliminary screening and to determine the teams that would receive site visits, each team was required to submit a 5-minute video that documented its progress toward development of an autonomous ground vehicle. DARPA received 136 video submissions; each was evaluated by at least two DARPA technical staff members using the following criteria:

- Compliance with Grand Challenge rules
- Suitability of vehicle platform for desert course
- Capability of sensor and navigation equipment
- Demonstration of navigation and sensor capabilities
- Potential to complete the Grand Challenge route

The results of the video evaluations and the video submissions were reviewed by DARPA senior management to ensure fairness and consistency in the selection process. DARPA selected 118 teams to receive site visits. Post-event assessment showed a significant correlation between teams that scored high on the video evaluation and their vehicle's ultimate performance on the Grand Challenge course. This result validated the use of the video demonstration in the selection process.

Site Visit. In May 2005, teams of two DARPA Government personnel conducted 2.5-hour site visits at locations chosen by the 118 teams selected for such reviews (Figure 2). Vehicles completed three runs on a standardized course of approximately 200 meters, including turns and obstacles. The vehicles were assessed on their ability to stay within course boundaries, detect and avoid obstacles, and navigate turns while maintaining a reasonable speed. The DARPA team also assessed the team's management plan, including approaches to personnel, planning, resources, and vehicle operations.

Figure 2. DARPA conducted 118 site visits to select teams for NQE.

This process produced quantitative and qualitative information that was used to compare and rank teams and their vehicles.

Upon completion of the site visits, 40 teams were invited to attend the NQE as Grand Challenge semi-finalists. In addition, DARPA selected nine teams as alternates to continue refining and testing their vehicles pending a second evaluation. Second-round site visits were conducted with the alternate teams in August 2005 and 3 additional teams were selected, resulting in 43 semi-finalists. The semi-finalist teams comprised more than 1,000 innovators who committed a significant portion of their personal time to advance state-of-the-art autonomous ground vehicle technology.

Site visit evaluations were well received by the teams as they offered the opportunity to demonstrate vehicle capabilities. Quantitative results from the site visit evaluations correlated well with vehicle performance at the NQE and GCE, validating this method for selecting the teams with the most potential for completing the Grand Challenge course.

Technical Paper. Each team was required to submit a technical paper describing its vehicle system architecture, sensor system, processing system, testing plan, and other technical specifications. The papers were openly published to enable technical interchange among teams and with others in the robotics community. The winning team's technical paper is included in Appendix C, and the full set is available on the Grand Challenge web site.

National Qualification Event (NQE). The NQE was held from September 28 to October 5, 2005, at the California Speedway in Fontana, California. The Speedway afforded the necessary facilities including garages, multiple practice areas, and a standardized test course on which vehicles could be evaluated (Figure 3).

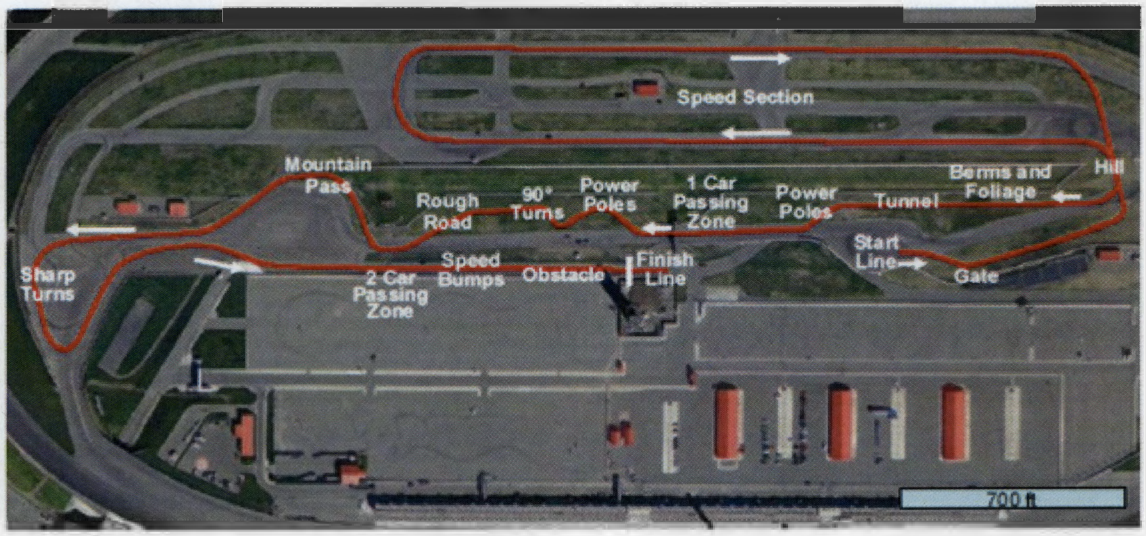

Figure 3. The NQE course layout showing the obstacles and other challenges faced by autonomous vehicles on the test course.

Prior to NQE, semifinalists were issued Government-owned emergency stop (E-stop) systems for integration with the autonomous vehicles. These units functioned as a wireless remote control switch to allow DARPA personnel to start and stop autonomous vehicles from a safe distance.

After an initial safety qualification and E-stop test, the vehicles' autonomous capabilities were evaluated on a test course in the infield area of the Speedway. The 2.5-mile route included waypoints with associated speed limits and route width and was provided to teams in advance. Course features were representative of the GCE desert course: a narrow opening (cattle gate), a relatively steep uphill/downhill section, a vehicle-passing test, and a 100-foot tunnel that blocked GPS signals. Each team was offered three or more opportunities to run the course. Vehicles were evaluated on their ability to remain within course boundaries, avoid obstacles, and finish as quickly as possible. Mojavaton—the first vehicle to attempt the course—completed it successfully, signaling that the group of teams at this Grand Challenge was significantly more advanced than the teams that competed in the 2004 event. Of the 43 teams that ran the NQE courses, 23 teams finished at least one test run and 5 teams completed all three runs.

In a feedback survey, participating teams characterized the NQE as an "inspiring" event. Beyond the ongoing competition, the garage area fostered productive technical interchange among the teams. High levels of commitment to success, interaction, and enthusiasm were evident throughout the NQE as teams worked 12+ hours a day to repair component failures and mechanical damage and ready vehicles for the next run.

Performance at the NQE and GCE was highly correlated; the top teams at NQE did well at GCE. This affirmed the validity of the evaluation methods used at NQE to select the finalists. On October 5, 2005, DARPA announced the 23 best-performing teams to travel to Primm, Nevada, and compete in GCE (see Table 1).

Table 1. Participants at NQE and their performance at GCE.

Ranking	Team Name	Hometown		GCE Distance Completed	Average Speed
1	Stanford Racing	Stanford	CA	132 miles	19.1 mph
2	Red Team	Pittsburgh	PA	132	18.6
3	Red Team Too	Pittsburgh	PA	132	18.2
4	Gray Team	Metairie	LA	132	17.5
5	Team TerraMax	Oshkosh	WI	132	10.2
6	Team ENSCO	Springfield	VA	81	
7	Axion Racing	Westlake Village	CA	66	
8	Virginia Tech	Blacksburg	VA	44	
9	Virginia Tech Rocky	Blacksburg	VA	39	
10	Desert Buckeyes	Columbus	OH	29	
11	Insight Racing	Cary	NC	26	
12	Team DAD	Morgan Hill	CA	26	
13	Mojavaton	Grand Junction	CO	23	
14	Golem Group / UCLA	Santa Monica	CA	22	
15	Team CajunBot	Lafayette	LA	17	
16	SciAutonics/Auburn Eng.	Thousand Oaks	CA	16	
17	CIMAR	Gainesville	FL	14	
18	IVST I	Littleton	CO	14	
19	Princeton University	Princeton	NJ	10	
20	Team Cornell	Ithaca	NY	9	
21	Team Caltech	Pasadena	CA	8	
22	MonsterMoto	Cedar Park	TX	7	
23	MITRE Meteorites	McLean	VA	1	
	A.I. Motorvators	Los Angeles	CA	NQE ONLY	
	Austin Robot Tech.	Austin	TX	NQE ONLY	
	AV Systems	San Diego	CA	NQE ONLY	
	Autonosys	Ottawa	CANADA	NQE ONLY	
	BJB Engineering	Willoughby Hills	OH	NQE ONLY	
	Blue Team	Berkeley	CA	NQE ONLY	
	CyberRider	San Juan Capistrano	CA	NQE ONLY	
	Indiana Robotic Nav.	Greenwood	IN	NQE ONLY	
	Indy Robot Racing	Indianapolis	IN	NQE ONLY	
	Oregon WAVE	Corvallis	OR	NQE ONLY	
	PV Road Warriors	Palos Verdes Estates	CA	NQE ONLY	
	Team AION	Carlsbad	CA	NQE ONLY	
	Team Banzai	Irvine	CA	NQE ONLY	
	Team Jefferson	Crozet	VA	NQE ONLY	
	Team Juggernaut	Sandy	UT	NQE ONLY	
	Team Overbot	Redwood City	CA	NQE ONLY	
	Team Tormenta	Los Angeles	CA	NQE ONLY	
	Team UCF	Orlando	FL	NQE ONLY	
	Team Underdawg	San Jose	CA	NQE ONLY	
	Terra Engineering	Rancho Palos Verdes	CA	NQE ONLY	

Grand Challenge Event (GCE). DARPA surveyed several possible routes for GCE and selected the course most representative of the operational conditions experienced by U.S. Joint Forces overseas. The Agency worked closely with the Nevada Bureau of Land Management to ensure compliance with local environmental and cultural restrictions and obtained a U.S. Fish and Wildlife Service Biological Opinion (in accordance with Section 7 of the Endangered Species Act of 1973, as amended) for the event.

Teams were informed of the general route area in August 2005 to enable travel plans. The specific route was revealed to the teams only 2 hours before their scheduled GCE start time. The general area surrounding the route was closed to teams starting on July 29, 2005, to ensure no participant had advance access to the actual route area.

The 132-mile route contained a series of graduated challenges beginning with a dry lake bed, narrow cattle guard gates, narrow roads, tight turns, highway and railroad underpasses. Travel surfaces included broken pavement, gravel utility roads, and off-road trails. The route featured more than 50 turns of at least 90 degrees, leaving only a slim margin of error for vehicle navigation systems. In many areas, vehicles that left the center of the route were quickly mired in soft sand or faced impassable conditions. Vehicles passed through tunnels and avoided more than 50 utility poles situated along the edge of the road. The route culminated with Beer Bottle Pass, which featured a steep, narrow downslope with a sheer drop-off on the side.

Course speeds varied from 10 mph in sections deemed unsafe for higher speed, to 40 mph on the dry lake bed. Completing the 132-mile route required approximately 6 hours at the defined course speeds. Each autonomous vehicle was monitored by DARPA via a real-time tracking system and was followed by DARPA personnel in a control vehicle equipped with an E-stop system. Vehicles were stopped if the DARPA Command Center or control vehicle crew determined a dangerous situation was developing.

The starting order was determined by the vehicles' performance at NQE, with the top performers starting first. The exception was TerraMax, which was started later in the order because of its large size and weight. Red Team Too was the first vehicle to start the route at sunrise (6:40 AM) on October 8, 2005 (Figure 4). Vehicles were launched at 5-minute intervals to ensure safe spacing, and their travel times were individually recorded using the E-stop system. The vehicles' ability to navigate, avoid obstacles, and stay within the route boundaries was tested throughout the course (Figure 5).

Stanford University's Stanley, the second vehicle to start, passed Red Team Too near the 100-mile marker and finished the course with the lowest time and highest average speed (19.1 mph). Red Team, Red Team Too, and Gray Team also completed the route successfully, well within the 10-hour limit at average speeds of 18.6, 18.2, and 17.5 mph, respectively. TerraMax was stopped at sunset (for control vehicle crew safety) approximately 80 miles into the route. DARPA officials determined TerraMax had a chance to finish the route within the 10-hour limit, and the vehicle was allowed to finish the route on the subsequent day, in accordance with Grand Challenge rules. TerraMax remained in autonomous mode overnight, with the engine running to provide power to the autonomous systems. The route was resumed at sunrise on October 9 and finished with an average speed of 10.2 mph.

Figure 4. A control vehicle (left) waits at the Grand Challenge start line, joining (from left) H1lander, Stanley, and Sandstorm. These vehicles finished third, first, and second, respectively.

Figure 5. Rugged terrain and dusty conditions tested the vehicles' capability to operate off-road.

TerraMax's overnight stay in the desert was the first recorded event in which a ground vehicle operated in autonomous operations for more than 24 hours without any human intervention other than to command the vehicle to stop and resume at sunrise and the addition of 5 gallons of diesel fuel.

The official results of the 23 competing teams are provided in Table 1. All but one vehicle exceeded the 7-mile distance achieved by the best vehicle in Grand Challenge 2004—a significant accomplishment.

6 PRIZE

The $2 million prize was awarded to the Stanford Racing Team on October 9, 2005, for its winning time of 6 hours, 53 minutes, 8 seconds (Figure 6)—approximately 11 minutes faster than the next vehicle to complete the route. The prize was funded from DARPA's Land Warfare Technology Program Element (0603764E), which has funded manned and unmanned advanced ground vehicles such as the Reconnaissance, Surveillance, and Tracking Vehicle and those for the Future Combat Systems (FCS) program.

Figure 6 Stanley, fielded by the Stanford Racing Team.

7 RESOURCES

The Grand Challenge was accomplished successfully through detailed planning and training and applying lessons learned from the 2004 event. Much of the equipment used (e.g., the E-stop system) was purchased for the 2004 event and refurbished and updated for use in 2005. Some infrastructure support for the event was unique to the program. The communications and tracking network necessary to ensure a safe event, for example, required the coordination of four hilltop tower sites spread over 500 square miles.

More than 200 staff personnel were used during the final 2 weeks of preparation, when NQE and GCE activities required 18-hour workdays. Personnel were utilized for track operations; in control vehicles; as E-stop master transmitter operators, environmental monitors, law enforcement personnel, route closure monitors, public affairs representatives, remote video technicians, and tow-truck operators; and in a 40-person operations center at the start/finish area (Figure 7).

Figure 7. Grand Challenge Operations Center.

The execution of NQE and GCE was an Agency-wide endeavor, involving approximately 100 Government personnel to perform essential functions before, during, and after the event. No Government staff was assigned to the Grand Challenge effort on a full-time basis, and contractors were used to plan and conduct the event.

DARPA expended approximately $7.8 million, plus the $2 million prize, for Grand Challenge 2005. The funds paid for contractor staff for overall planning and execution; site visits; route selection surveys and route preparation; area biological surveys and monitoring; control and autonomous vehicle communications and tracking networks; NQE setup, execution, and clean-up; GCE setup, execution, and clean-up; Government-furnished electronics systems for vehicle control; and lease and equipment updates of 30 pickup trucks used as control vehicles.

8 TRANSITION

In December 2005, DARPA, with the assistance of the Military Services, displayed the five vehicles that finished the Grand Challenge in the inner courtyard of the Pentagon (Figure 8). Through events such as this, the Grand Challenge has served to promote acceptance of unmanned ground systems within the Defense community, much as unmanned air vehicles have come to be accepted as essential partners in the air.

Figure 8. Grand Challenge technology on display in the Pentagon courtyard in December 2006.

Some teams have plans to transition technology developed for the Grand Challenge directly to the marketplace. Oshkosh Truck Corporation, owner of Terramax, has transitioned technology developed for the Grand Challenge to the Palletized Load System (PLS) Unmanned Ground Vehicle (Figure 9). This system was demonstrated on January 23, 2006, at the U.S. Army Tactical Wheeled Vehicle Component Technology Demonstrations in Yuma, Arizona. The PLS, with onboard material handling and a 16.5-ton payload capacity, is designed to transport containers carrying ammunition and other critical supplies or large tanks holding fuel or water. The original platform has been used in military operations in Bosnia, Kosovo, Afghanistan, and Iraq.

Figure 9. Oshkosh transitioned technology developed for Grand Challenge 2005(left) to its Palletized Load System Unmanned Ground Vehicle (right).

The Red Team used a gimbaled sensor with fiber optic gyroscopes mounted to stabilize the light detection and ranging (LIDAR) system against vibration of the underlying platform. HD Systems (Happauge, New York) plans to market a miniaturized version of this technology for use in satellites and DoD weapons systems. Technology developed for the Grand Challenge is expected to be available for both FCS and commercial systems, such as those manufactured by General Motors, another key Red Team sponsor.

Teams are exploring possible transition opportunities within the National Security and Homeland Defense communities as well, including remote infrastructure patrol and inspection, boundary patrol, automated runway clearing, use as targeting drones, and traditional military applications such as scout and convoy vehicles that are part of the FCS program. Several participants are already well-connected with existing military programs, and the program results are expected to influence the work being done for DoD.

A wide range of technical innovations was demonstrated for the Grand Challenge, including many subsystems. Figure 10 shows a novel 64-sensor configuration, developed and demonstrated by Team DAD from Morgan Hill, California. A rotating LIDAR system was designed to create a low-cost system capable of full azimuthal coverage operating at an update rate needed by a moving vehicle. Team DAD is exploring interest among military customers.

Figure 10. Rotating multiple LIDAR system from Team DAD.

The Indy Robot Racing Team demonstrated a plug-and-play system for sensors that involved a network protocol for autonomous driving. This type of capability will be essential as autonomous systems advance and grow in complexity.

Beyond advancing militarily relevant technologies, the competition format stimulated interest and excitement in a problem area important to DoD, broadened the technology base, and strengthened U.S. capability to develop autonomous ground vehicle technologies

9 CONCLUSION

In addition to the many technical accomplishments, media coverage for Grand Challenge 2005 was an essential part of program impact. Stories about various aspects of Grand Challenge ran in essentially all major U.S. news outlets including *The New York Times*, *The Washington Post*, *The Wall Street Journal*, United Press International, and Associated Press; news outlets through Europe and Asia; and broadcast outlets such as CNN and The Discovery Channel. Mass media science magazines including *Scientific American, Discover,* and *Popular Science* ran full articles, and Public Broadcasting Service's NOVA developed a one-hour show dedicated to the Grand Challenge. This widespread media coverage increased awareness about a DoD technology interest area among the general public. Since the Grand Challenge, DARPA program managers have received numerous new proposals and inquiries about DARPA programs from individuals who have not previously done business with DARPA.

The lead news story has been the remarkable improvement in vehicle performance in just 19 months from the first Grand Challenge in March 2004 to the second Grand Challenge in October 2005. Because of the competitive environment created by the prize authority, teams progressed from vehicles able to complete only 5 percent of the route to four vehicles finishing the course within the 10-hour limit. This rapid technology improvement in the areas of sensors, navigation, control algorithms, hardware systems, and systems integration has drawn the attention of journalists and scientists around the world and changed perspectives on autonomous ground vehicle technology capabilities.

All the vehicles that attempted the Grand Challenge were mechanically capable of finishing the route at a relatively high speed. The competition was in large measure a software race that tested the ability of teams to define and implement produce robust software systems able to adapt and "learn" the sensor signature of navigable versus impassable terrain through repeated exposure. While the results are applicable specifically to autonomous vehicle navigation, the success of the learning-based approach in this real-world context will impact other domains of machine learning and cognition, immediately and in the future.

The 132-mile Grand Challenge route was chosen as representative of military re-supply missions, and the achievements of the vehicles that completed the route can be said to demonstrate conclusively that autonomous vehicle are able to travel over rugged terrain at militarily relevant distances and speeds. This successful technology demonstration has changed thinking about autonomous ground vehicle capabilities. An autonomous vehicle that can operate safely in all environments remains a challenge, however, as future military missions will require unmanned vehicles that can operate closely with mounted and dismounted personnel in complex environments such as urban terrain.

The prize awarded to the winner clearly reflects the intent of Congress, to recognize "outstanding achievement in basic, advanced, and applied research, technology development, and prototype development that has the potential for application to the performance of the military missions of the Department of Defense". The use of the prize authority attracted thousands of inventors to work in an area important to DoD.

The Grand Challenge has had a tremendous influence in sparking interest in the problems of DoD robotics and has inspired students and researchers to pursue careers and opportunities in this area. Applicants to participant universities are specifically citing the Grand Challenge in their engineering graduate school applications, suggesting the pervasive influence the event has had, and will have, in stimulating technical work in this area.

APPENDIX A

SECTION 2374a OF TITLE 10 OF THE UNITED STATES CODE

§ 2374a. Prizes for advanced technology achievements

(a) Authority. The Secretary of Defense, acting through the Director of the Defense Advanced Research Projects Agency, 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.

(b) Competition requirements. The program under subsection (a) shall use a competitive process for the selection of recipients of cash prizes. The process shall include the widely-advertised solicitation of submissions of research results, technology developments, and prototypes.

(c) Limitations.

(1) The total amount made available for award of cash prizes in a fiscal year may not exceed $10,000,000.

(2) No prize competition may result in the award of more than $1,000,000 in cash prizes without the approval of the Under Secretary of Defense for Acquisition, Technology, and Logistics.

(d) Relationship to other authority. The program under subsection (a) may be carried out in conjunction with or in addition to the exercise of any other authority of the Director to acquire, support, or stimulate basic, advanced and applied research, technology development, or prototype projects.

(e) Annual report. Promptly after the end of the 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 application 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.

(f) Period of authority. The authority to award prizes under subsection (a) shall terminate at the end of September 30, 2007.

APPENDIX B

SECTION 257 OF THE NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 2006

SEC. 257. MODIFICATION OF REQUIREMENTS FOR ANNUAL REPORT ON DARPA PROGRAM TO AWARD CASH PRIZES FOR ADVANCED TECHNOLOGY ACHIEVEMENTS.

Subsection (e) of section 2374a of title 10, United States Code, is amended to read as follows:

(e) Annual Report — (1) Not later than March 1 each year, the Secretary shall submit to the Committees on Armed Services of the Senate and the House of Representatives a report on the activities undertaken by the Director of the Defense Advanced Research Projects Agency during the preceding fiscal year under the authority of this section.

(2) The report for a fiscal year under this subsection shall include the following:

(A) The results of consultations between the Director and officials of the military departments regarding the areas of research, technology development, or prototype development for which prizes would be awarded under the program under this section.

(B) A description of the proposed goals of the competitions established under the program, including the areas of research, technology development, or prototype development to be promoted by such competitions and the relationship of such areas to the military missions of the Department.

(C) The total amount of cash prizes awarded under the program, including a description of the manner in which the amounts of cash prizes awarded and claimed were allocated among the accounts of the Defense Advanced Research Projects Agency for recording as obligations and expenditures.

(D) The methods used for the solicitation and evaluation of submissions under the program, together with an assessment of the effectiveness of such methods.

(E) A description of the resources, including personnel and funding, used in the execution of the program, together with a detailed description of the activities for which such resources were used.

(F) A description of any plans to transition the technologies or prototypes developed as a result of the program into acquisition programs of the Department.

APPENDIX C

STANFORD RACING TEAM'S TECHNICAL PAPER, 2005 DARPA GRAND CHALLENGE

Stanford Racing Team

Email: srt@cs.stanford.edu
Web: www.stanfordracing.org

Abstract

The Stanford Racing Team (SRT) has successfully developed an autonomous robotic vehicle capable of driving through desert terrain without human intervention. The SRT vehicle Stanley is based on a reinforced Volkswagen Touareg, equipped with a custom drive-by-wire system, a sensor rack, and a computing system. The vehicle is controlled through a distributed software system that uses inertial sensing for pose estimation, and lasers, vision, and RADAR for environmental perception. Sensor data is mapped into a drivability map, which is used to set the direction and velocity of the vehicle. A major emphasis of the SRT has been early development of a prototype end-to-end system, to enable extensive testing in authentic desert terrain.

1. PROJECT OVERVIEW

The Stanford Racing Team (SRT) is Stanford's entry in the 2005 DARPA Grand Challenge. The SRT brings together leading automotive engineers, artificial intelligence researchers, and experienced program managers, to develop the next generation of self-driving vehicles. The SRT has developed a robotic vehicle dubbed "Stanley," which has been selected as a semifinalist by DARPA.

The SRT leverages proven commercial off-the-shelf vehicles with advanced perception and driving systems developed by the Stanford AI Lab (SAIL) and affiliated researchers. The strong emphasis on software and vehicle intelligence indicates the SRT's belief that the DARPA Grand Challenge is largely a software competition. As long as the vehicle stays on the road and avoids obstacles, commercial SUVs are fully capable of negotiating the terrain. The challenge, thus, has been to build a robust software system that guides the vehicle in the right direction at the appropriate speed.

The SRT software system employs a number of advanced techniques from the field of artificial intelligence, such as probabilistic graphical models and machine learning. Following methodologies described in [3], The SRT has also developed novel estimation and control methods specifically suited to driving at moderate speeds through unrehearsed terrain. The software is housed in a state-of-the-art commercial off-road vehicle, appropriate modified to provide precision navigation under computer control.

From the beginning of this project, the SRT has placed a strong emphasis on in-field development and testing. Initial tests of a preliminary end-to-end system took place in December 2004. Since this time, Stanley has logged many hundreds of autonomous miles.

This article provides a high-level overview of the various system components, at a level suitable for broad public dissemination. Further material can be found on the team's Web site, at **www.stanfordracing.org**.

The goal of the Stanford Racing Team is to develop a vehicle that can finish the 2005 DARPA Grand Challenge within the allotted time. Through this research, the SRT also hopes to make driving safer, by advancing the state-of-the-art in vehicle navigation and driver assistance systems. The SRT believes that the technologies developed in this project can enhance the awareness of drivers and their vehicles, and enhance the safety of vehicular traffic.

2. TEAM COMPOSITION AND SPONSORSHIP

The SRT formed in July 2004, but continued to grow for the six months that followed. The team consists of approximately 50 individuals that include Stanford students, faculty, and alumni, and employees of the SRT primary supporters and other nearby research labs. The team's overall lead is a faculty member in the Stanford Artificial Intelligence Lab, a unit of Stanford's School of Engineering.

The team is comprised of four major groups: The Vehicle Group oversees all modifications and component developments related to the core vehicle. This includes the drive-by-wire systems, the sensor and computer mounts, and the computer systems. The group is led by researchers from Volkswagen of America's Electronic Research Lab. The Software Group develops all software, including the navigation software and the various health monitor and safety systems. The software group is led by researchers affiliated with Stanford University. The Testing Group is responsible for testing all system components, and the system as a whole, according to a specified testing schedule. The members of this group are separate from any of the other groups. The testing group is led by researchers affiliated with Stanford University. The Communications Group manages all media relations and fund raising activities of the SRT. The communications group is led by employees of Mohr Davidow Ventures.

The SRT is sponsored through four Primary Supporters: Volkswagen of America's Electronic Research Lab, Mohr Davidow Ventures, Android, and Red Bull. The Primary Supporters together with the Stanford team leaders form the SRT Steering Committee, which oversees the SRT operations. The SRT has also received support from Intel Research, Honeywell, Tyzx, Inc., and Coverty, Inc. Generous financial contributions were made by David Cheriton, the Johnson Family, and Vint Cerf.

3. VEHICLE DESCRIPTION

Figure A.1: Stanley is based on a 2004 Volkswagen Touareg R5 Diesel. The vehicle is equipped with a number of sensors for environment perception and localization.

The Stanley vehicle is based on a stock Volkswagen Touareg R5 with variable-height air suspension (Figure A.1). The Diesel-powered vehicle was selected for its fuel efficiency and its ability to negotiate off-road terrain. To protect the vehicle from environmental impact, the vehicle is outfitted with custom skid plates and a front bumper.

The Volkswagen Touareg R5 is natively throttle- and brake-by-wire. A custom interface to the throttle and braking system enables Stanley's computers to actuate both of these systems. An additional DC motor attached to the steering column provides the vehicle with a steer-by-wire capability. Vehicle data such as the individual wheel speeds are sensed automatically and communicated to the computer system through a custom CAN bus interface. The Touareg's alternator provides all power for the various computing and sensing systems.

The vehicle's custom-made roof rack holds most of Stanley's sensors. For environment perception, the roof rack holds five SICK laser range finders pointed forward into the driving direction of the vehicle, a color camera which is also pointed forward and angled slightly downwards, and two antennae of a forward-pointed RADAR system. A number of antenna are also attached to the roof rack, specifically one antenna for the GPS positioning system, two additional GPS antennae for the GPS compass, the communication antenna for the DARPA emergency E-Stop, and a horn and a signal light, as required by the DARPA Grand Challenge rules. Three additional GPS antenna for the DARPA E-Stop are directly attached to the roof.

The computing system is located in the vehicle's trunk, as shown in Fig A.2. Special air ducts direct air flow from the vehicle's AC system into the trunk for cooling. The trunk features a shock-mounted rack that carries an array of six Pentium M Blade computers, a Gigabit Ethernet switch, and various devices that interface to the physical sensors and the Touareg's actuators. It also features a custom-made power system with backup batteries and a switch box that enables Stanley to power cycle individual system components. The DARPA-provided E-Stop is also located on this rack, on additional shock compensation. A 6 degree of freedom (DOF) inertial measurement unit (IMU) is rigidly attached to the vehicle frame underneath the computing rack in the trunk.

Figure A.2: Left: The computing system in the trunk of the vehicle. Right: The drive-by-wire system and the interface for manual vehicle operation.

4. AUTONOMOUS OPERATIONS

Autonomous navigation is achieved through a processing pipeline that maps raw sensor data into an internal state estimate. The internal state is comprised of a number of variables, relating to the vehicle's location, the workings of the various hardware components, and the location of obstacles in the environment.

4.1. Localization

At any point in time, the vehicle is localized with respect to a global UTM coordinate frame. Localization also involves the estimation of the vehicle's roll, pitch, and yaw angles. Stanley achieves its localization through an unscented Kalman filter (UKF) [1], which is a non-linear version of the Kalman filter. The UKF asynchronously integrates data from the GPS systems, the IMU, and the CAN bus, at a maximum update rate of 100 Hz. It utilizes a "bicycle model" for accurate position estimation during GPS outages. The output of the UKF is a stream of 6-D estimates of the vehicle position and Euler angles along with uncertainty covariances.

The localization module enables the vehicle to map the global RDDF file into local vehicle coordinates. To accommodate the residual uncertainty in the location estimates, the width of the RDDF corridor is dynamically adjusted in proportion to this uncertainty. As a result, the vehicle can accommodate moments of high position uncertainty.

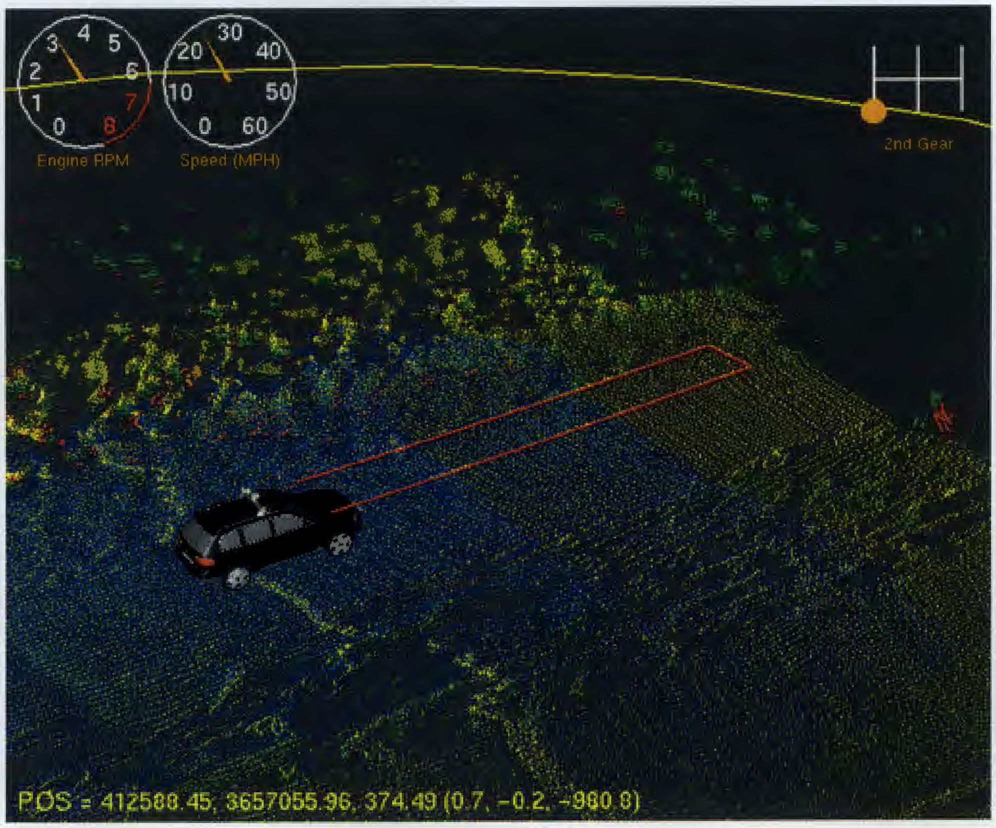

Figure A.3: Laser data; see text.

4.2. Sensor Processing

Environmental sensing is achieved through the three different sensing modalities: laser, vision, and RADAR. Each of these systems is characterized by a different trade-off between range and accuracy.

The laser system provides accurate short-range perception, up to a range of approximately 25 meters. This range is sufficient for slow motion, but insufficient for the speeds required to win the Challenge. To enable faster motion, Stanley relies on two complementary systems, a camera and a RADAR system. The camera provides an enhanced range relative to the laser, and it captures denser data than each individual laser. However, the camera does not provide range data. The RADAR system provides range data for a range of up to 200 meters, but at a level of coarseness far inferior to the laser measurements.

The software system geo-references all raw sensor data by the UKF position estimates in global UTM coordinates. The laser data is continually analyzed for possible obstacles, defined as rapid elevation changes exceeding a height of 15cm. A temporal Markov chain is used to model the temporal information loss in the data acquisition process; and the Markov chain error terms are considered in the assessment of surface ahead. The specific functions involved in detecting obstacles are determined through a machine learning algorithm, which relies on human driving to acquire "training examples" of drivable terrain. See Figure A.3 for typical laser data. The coloring in this figure corresponds to different physical laser sensors.

The vision processing module relies on an adaptive filter to discriminate the road ahead from obstacles near the road. The filter classifies the terrain based on texture and color appearance of the desert terrain within the camera image. Using online machine learning, the vision module continually adapts to different terrain types, using near-range data classified by the lasers to determine the current best model of the road surface. This adaptation takes place at a rate of 8Hz. Rectification into UTM coordinates is achieved through a projective formula that makes an implicit planar world assumption.

The RADAR data is processed through a proprietary algorithm that identifies large obstacles in the environment. A temporal filter tracks individual singular obstacles over time, to reduce the false positive rate. RADAR data is mapped into the drivability map under a flat ground assumption.

4.3. Environmental Mapping

The data of all these three sensors is integrated into a single model of the environment, called the drivability map. Each cell in this 2-D map assumes one of three values: unknown, drivable, or not drivable. The exact value is a function of the sensor data received for this cell. The map is referenced in global coordinates, though for computational reasons only a small window is retained at any point in time. The drivability map is updated asynchronously for the different sensor types, at rates that vary from 8Hz to 75Hz. As the vehicle moves, the map is shifted so as to always contain all cells within a fixed margin around the vehicle.

Figure A.4 illustrates the drivability map. Shown there is the vehicle within its local environment. White grid cell correspond to drivable terrain; red cells to obstacles; and grey cells to unknown terrain. A rolling grid focuses the map on the relevant area around the vehicle.

To ensure consistency of this map, the sensors are periodically calibrated using data of dedicated obstacles of known dimensions. Calibration is an offline process which involves human labeling of sensor data. The calibration process adjusts the exact pointing directions of the individual sensors by minimizing a quadratic error, defined through multiple sightings of the same calibration obstacle.

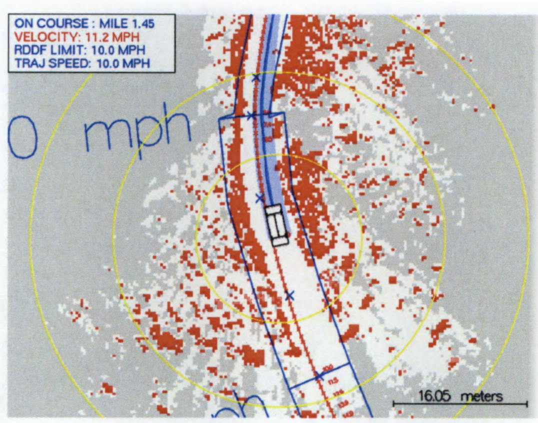

Figure A.4: A typical drivability map.

4.4. Road Condition Estimates

In addition to the drivability map, the system also estimates a number of other variables pertaining to the general condition and structure of the environment. In particular, Stanley utilizes estimators of the terrain ruggedness, the terrain slope, and the left and right road boundaries. All of those estimates are implemented as low-pass filters on data directly derived from the sensor measurements. They are used to set the driving direction and the velocity of the vehicle.

The SRT robot also uses a detector for dead ends. While dead ends are generally unlikely to occur in the context of the 2005 DARPA Grand Challenge, they still may occur when disabled vehicles block parts of the road. The dead end detector is a high-pass filter on the drivability map; its main function is to initiate back-ups.

5. VEHICLE CONTROL

The state estimates are used to determine the three primary vehicle controls: the steering, throttle, and brake. It also controls the gear shifter.

The vehicle control system is implemented through three primary control systems, operating at different levels of temporal and spatial abstraction: a PID controller, a path planning algorithm, and a finite state automaton.

5.1. PID Motion Control

The PID controller accepts as input a reference trajectory provided by the path planning algorithm, and the vehicle state as provided by the Kalman filter. The PID controller generates steering and velocity controls that are executed by the vehicle. It is updated at a frequency of 20Hz.

The steering controller operates by minimizing the lateral offset to a desired trajectory provided by the path planer, with additional terms addressing steering wheel lag and vehicle drift. The velocity controller adjusts the brake pressure and the throttle position so as to attain a velocity commanded by the path planning module. The control module supports forward and backward motion.

5.2. Path Planning

The path planning module accepts as input the drivability map and the estimated robot pose, along with the corridor boundary from the RDDF file. The path planning module produces as output a reference trajectory suitable for vehicle control. This trajectory is determined by trading off five primary control objectives: The number of non-drivable cells along a path, the clearance to nearby obstacles, the nearness to the road center, the proximity to the adjusted RDDF corridor boundary, and the amount of lateral acceleration necessary to attain a given trajectory. By trading off these five different measures, the vehicle tends to identify paths that are safe to drive, within the RDDF corridor, and that maximize progress. Path planning takes place at a frequency of 10Hz.

The path planning module also sets the target velocity of the vehicle. The velocity controller runs at 10Hz. During every iteration, it generates a target trajectory that is communicated to the controller. The target velocity is obtained as a function of a number of criteria. Specifically, Stanley always assumes an allowable velocity according to pre-processed RDDF file, and it slows down in curves so as to retain the ability to avoid unexpected obstacles. The vehicle also adapts its velocity to the roughness of terrain, and to the nearness of obstacles. The specific transfer function emulates human driving characteristics, and is learned from data gathered through human driving.

To attain a suitable trajectory and associated maximum velocity, the RDDF file is processed by a smoother. The smoother adds additional via points and ensures that the resulting trajectory possesses relatively smooth curvature. The preprocessing then also generates velocities so that while executing a turn, the robot never exceeds a velocity that might jeopardize the vehicle's ability to avoid sudden obstacles. This calculation is based on a physical model of the actual vehicle.

5.3. State Automaton

The highest level of control is implemented through a finite state automaton (FSA). The FSA monitors the various state and road condition estimates to determine the principal driving mode of the vehicle. Driving modes include modes of forward motion, stopping, gear shifting, and backing up. The back up mode is used when the vehicle planner determines that all forward vehicle paths would result in a collision.

The FSA provides the highest level of vehicle control. It also implements the various steps necessary to react to a pause command by the DARPA team.

5.4. Software System

The various elements of the Stanley software system are all embedded into a large distributed architecture. The software is broken down into modules, each of which establishes an individual process on one of Stanley's computers. These processes are run asynchronously on a distributed array of six Pentium M Blade computers. The clocks of these computers are constantly synchronized to ensure consistent time stamping. All inter-module communication is provided through the publicly available open source Inter Process Communication (IPC) package [2]. The IPC enables different modules to communicate via TCP/IP messages over the local Ethernet.[‡] All software is written in C/C++. The operating system is Linux. Software verification is achieved with the help of code analysis tools developed by Coverty, Inc.

‡ Written permission to use this publicly available software package was obtained from DARPA within the applicable deadline.

The software system possesses a number of data logging and display modules. Most of the sensor and control data is logged during major system tests. The visualization routines operate equally on live and logged data. The software also utilizes a centralized parameter server which ensures global consistency.

The software architecture also provides a number of safety and recovery mechanisms to accommodate component failure. A dedicated watchdog module monitors all primary hardware and software components for possible malfunctioning. It power-cycles hardware components and restarts software modules when necessary. As a result, the system can survive failures of individual modules and system components.

6. VEHICLE SAFETY

Safety has been of utmost importance in the design of the vehicle system.

E-stop pausing is handled through Stanley's software system. When a pause command is issued, the FSA directs the vehicle to come to a prompt stop and shifts the vehicle into park until a run command is issued.

The disable command is connected to the vehicle engine control, bypassing Stanley's computing pipeline. A disable command results in brake actuation and a prompt shutdown of the engine. By directly connecting the disable mechanism to the Touareg engine system, malfunctioning of the computer pipeline cannot affect the functioning of this essential safety feature.

The vehicle is equipped with a siren and a strobe that fully comply with the regulations stated in the 2005 DARPA Grand Challenge Rule document. The vehicle is also equipped with two latching E-stop buttons.

Despite these modifications, Stanley remains fully street legal and can be operated manually. Switches mounted near the driver console enable a human operator to seamlessly transition between manual and computer-controlled operation, even while the vehicle is in motion. While this feature is not necessary for the actual Grand Challenge event, it ensures the safety of vehicle occupants during testing.

7. SYSTEM TESTS

Testing has played a major role in the development of the Stanford Racing Team robot Stanley. Primary testing areas include terrain in the Mojave desert, including parts of the 2004 DARPA Grand Challenge Course, a vehicle testing facility in Arizona and nearby public lands, and local terrain at and near Stanford University.

In the initial months from December 1, 2004, to July 28, 2005, testing took place within month-long development cycles that combined three weeks of core development with a week-long testing event in the Mojave Desert. Since the beginning of August 2005, the system is being tested full time in Arizona.

From the very beginning of this project, the team pursued a sequence of milestones, most of which were met. The major milestones were as follows:

- December 1, 2004: First fully autonomous desert mile (achieved: December 1, 2004; the vehicle traversed the first 8.5 miles of the original 2004 DGC course before the autonomous run had to be terminated).
- February 1, 2005: Waypoint navigation at race speed (achieved: February 13, 2005).
- April 1, 2005: Five autonomous miles at an average speed of 25mph with full collision avoidance (achieved April 11, 2005, along an easy section of the 2004 DGC course).
- May 10, 2005: DARPA Site visit, which led to the selection of the team as one of the 40 semi-finalists.
- July 1, 2005: Autonomous traversal of the entire 2004 DARPA Grand Challenge Course, with the exception of public roads (partially achieved July 16, 2005; the team encountered a total of six failures, each at a level that would have been fatal in an actual race).
- September 11, 2005: 200 uninterrupted autonomous miles over unpaved deser roads at the final racing speed.

Some of the testing is performed through a dedicated vehicle testing group. Since August 20 the emphasis has been on endurance testing of the integrated end-to-end system in realistic desert terrain.

8. CONTACT

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