14065 14065

Paper Number

Insider's View of the 2004 DARPA Grand Challenge

Robert T. Kania, Philip A. Frederick, Jeff Jaczkowski
RDECOM TARDEC VETRONICS Autonomous Navigation Team

ABSTRACT

The DARPA Grand Challenge was a competition between autonomous ground vehicles racing between Los Angeles and Las Vegas in March of 2004. According to DARPA "The purpose of the challenge is to leverage American ingenuity to accelerate the development of autonomous vehicle technologies that can be applied to military requirements". This paper focuses on some of the innovations, in mobility and perception, utilized on vehicles at the competition from the perspective of DOD volunteers involved with vehicle inspection, start line qualification, vehicle following, and finish line verification.

INTRODUCTION

What constitutes an autonomous vehicle? Webster defines autonomous as "undertaken or carried on without outside control". Is autonomy simply a measure of getting from point A to point B unattended? Or is it something deeper? Under Webster's definition, a child jumping of their bike to watch it travel; would be launching an autonomous vehicle. Of course that line of reasoning is in error. Perhaps it is the methodology of getting form A to B that defines autonomy. Perhaps the decisions made while interacting *with* the environment are more important then the resulting actions of traveling *through* the environment.

The authors believe this to be the case; that DARPA, seeking intelligent interaction with the environment, set the bar quite high considering the current state-of-the-art. What they received in the form of the Grand Challenge was a cadre of vehicles ranging from "a brick on the accelerator" to a priori preemptive path planning.

THE DARPA GRAND CHALLENGE

ON YOUR MARK...

What was the Grand challenge?

The DARPA Grand Challenge was originally touted as an 'Autonomous race across the desert.' As exciting as this may sound, Nevada state law prohibits racing in the desert; so it became a field test that required robotic ground vehicles to successfully navigate a course from Barstow, CA to Primm, NV as quickly as possible under 10-hours.

On Saturday, March 13, 2004 the robots were brought out to the start line and positioned in their chutes. The robots would start one at a time and the cement chutes would protect them from one another should something unfortunate happen. The course would cover 142 miles of on- and off-road terrain (mostly secondary roads) that was cleared of all non-participants (except the occasional dirt bike enthusiast.) Hours before the start time, the competitors were given a map that contained GPS waypoints for their vehicles to follow that specified geographic locations, speed limits, and boundaries that the vehicle must traverse and avoid. The robots were followed by chase-vehicles that consisted of a driver, a DARPA PM representative (judge), and a government communications operator. This vehicle was responsible for the safe operation of the robot. The chase team had limited control of the robot through an emergency-stop system that could start, stop, and disable the robot.

In the week prior to the event, March 8th thru 12th, Qualification, Inspection, and Demonstration (QID) took place. QID had two major goals. First, the teams needed to show they had the potential to actually successfully accomplish the event. This was done by running in a scaled-down version or the course mocked up at the California Motor Speedway. Second, and more importantly, they needed to prove their vehicle could operate in a safe and controlled fashion. This seems intuitive, but when you consider teams like Terramax (dubbed Big Bertha), it becomes paramount. At the end of QID DARPA announced that mosth teams were eligible to compete in the event on Saturday.

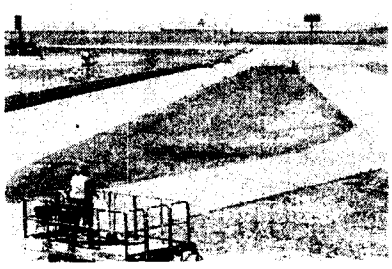

Figure 1: California Motor Speedway

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
02 JUN 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Insider's View of the 2004 DARPA Grand Challenge	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Robert T. Kania; Philip A. Frederick; Jeff Jaczkowski	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
USA TACOM 6501 E 11 Mile Road Warren, MI 48397-5000	**14065**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	TACOM TARDEC
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
U.S. Government Work; not copyrighted in the U.S. Presented at NDIA Conference June 21, 2004

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**8**	

Why did DARPA host this event?

In the words taken from the challenge's homepage: "The purpose of the DARPA Grand Challenge is to leverage American ingenuity to accelerate the development of autonomous vehicle technologies that can be applied to military requirements."

The consensus from the DARPA officials at the event was that this would hopefully spur innovation in the field of autonomous ground vehicles. Although the competitors were not legally indebted in any fashion, the hope was that any resulting technologies developed would be made available at a fair-market price.

Lindbergh's pioneering trans-Atlantic flight was cited as an example of a successful competition on this nature.

Why did teams rise to the challenge?

Although the vast majority of the teams questioned first mentioned altruistic reasons such as "furthering the knowledge base of autonomous ground vehicles," or "advancing the state of the art in visual perception technologies;" not one team failed to mention the $1,000,000 bounty. So although their motivations were as diverse as their bots, they all had one common motivation – win the money!

For many of the teams, like CMU that has been doing work of this nature for the better part of a decade, this was just another venue to test and showcase their technologies. For others, this was a chance to be the star of *Monster Garage*. Whatever their reasons, they all came out in full force and by QID there were 22 competitors ready for action. It should be mentioned that these 22 had already won their first victory by being invited to QID. They were narrowed down from the over 100 teams that had solicited white-papers requesting to compete.

Who were the competitors?

Although it is quite difficult to categorize the 22 competitors in such a fashion that there isn't overlap or room for conjecture, the following groups will suffice for this paper.

"Sure Things"

These were the high profile teams that tended towards solid funding, advanced methodology, strong university ties, etc...

- The Red Team (Carnegie Mellon University)
- SciAutonics II
- Team CalTech
- Team TerraMax
- Team CIMAR (University of Florida)

"Dark Horses"

These are the teams with unknown and unproven technological approaches that ended up with similar results to those expected of the "sure things."

- Digital Auto Drive
- The Golem Group
- SciAutonics I

"Underachievers"

This is where teams were placed, when they gave a strong show in QID but fell short on the day of the event.

- Virginia Tech
- Axion Racing
- Team ENSCO

"Mechanically Focused"

Teams that demonstrated a noticeable focus on intrinsic mobility over vehicle intelligence were placed in this group.

- Team Terrahawk
- Team CajunBot (University of Louisiana at Lafayette)
- Rover Systems

"Media Darlings"

These teams were lacking in everything but camera appeal.

- Palos Verdes High School Road Warrior
- The Blue Team (Berkeley)

"Garage Teams"

These were the teams that appeared to have vastly underestimated the difficulty of this endeavor and fell short in funding, manpower, methodology, etc...

- Team Phantasm
- Team LoGHIQ
- AI Motorvators
- The Spirit of Las Vegas

"No Show"

Teams that failed to attempt QID or the event were placed here.

- Team CyberRider
- Rob Meyer Productions

GET SET...

The science behind the show

No matter what the outcome on competition day, it's the technology developed and matured that's of interest. To this end, we've tried to cover every team's key technologies and to call out anything that may have been unique to them or given them a noticeable edge. The information that follows comes directly from the team's technical reports and interviews with their crew members, as well as, the observations, notes, and opinions of the authors'.

"Sure Things"

These teams focused on high-level activities such as terrain mapping, advanced navigation, and sensor fusion. They had an obvious edge because of prior experience in the field, already proven technologies, and ties to academia doing related research. Most had vehicles evolved past the point of platform-development problems such as drive-by-wire or brake-by-wire interfacing.

The key enabling technology behind the Red Team and SciAutonics II was a priori terrain mapping. Both teams acquired Digital Terrain Elevation Data (DTED) maps of the entire event course, as well as ran the course testing for ground truth, weeks before the event. Based on the QID observations from their two runs, it appeared the Red Team likely even mapped the QID course before their first run. SciAutonics II seemed to be building their QID database as they went. Each run would speed to where they left off on the previous attempt, and then slowly proceed. This was obviously a solid approach since these teams were the top two qualifiers.

CalTech's key enabling technology was a navigation system based on an arbitrator that fused the sensor data from Laser Detection And Ranging (LADAR), Global Positioning System (GPS), and Inertial Measurement Unit (IMU) systems. This arbitrator took the data from eight navigation modules along with confidence values to determine an optimal path. Again, this was a solid approach that qualified them at number three.

TerraMax had a "Surround Sensing/Sensor Fusion Module" that was central to its control strategy. This system gave the vehicle 360° perceptual awareness and fed their low-level reactive obstacle avoidance. This approach would have qualified them at seventh, but concern over moving them should they become impaired during the race, relegated them to twelfth.

Team CIMAR had a Planning Element Knowledge Store (PKS) that made it stand out. They took generated path segments and placed them in the store. The store would then release them, two segments at a time, to the Path Segment Driver (PSD); which would then perform closed loop position and velocity control to move along the given path segments. This approach placed them 9th in the qualification standings.

"Dark Horses"

These competitors had appearances that belied their capability. First impressions would not have placed them high in the standings, but their results spoke for themselves.

The Digital Auto Drive (DAD) vision system was the major technical thrust of their project. It's key enabler was a custom camera system that directly feeds image data to three Digital Signal Processors (DSP) which dramatically reduces acquisition time. This was essential because their entire system was vision based without the use of any other sensors. This innovative technology placed them 4th after qualifications.

Vision and Radar were the primary technologies that fueled The Golem Group. The multiple sensor input was mainly redundant, but limited data fusion was attempted. Although competition day results would show otherwise, initial qualification results would place their vehicle at the end of the competency list at 14th.

The most notable aspect of SciAutonics I was the software architecture centering on their RASCAL Brain Module. This interfaced with 4 SICK LADARS, arranged in a box-formation for terrain mapping, a magnetometer, and an INS system. All this worked together to land them the 11th spot after qualifications.

"Underachievers"

Some of the teams appeared to have everything going for them – sound methodology, well developed systems, and quality people at the helm. Yet when it came down to performance time; things just didn't work out.

Virginia Tech implemented a robust distributed computing system from National Instruments that networked their Laser Range Finders, RADAR, and Cameras. This COTS solution landed them 5th after

qualifications and held the promise of a solid show come event day.

The Axion Racing team featured a ruggedized rack system housing five shock-mounted Pentium class servers and one National Instruments Compact Field Point system. All the systems implemented in these servers were linked to a central processing module called the Arbitrator. Like, VA Tech, their impressive solution placed them high in qualification, 6th place, with promise of more to come.

Team ENSCO used preemptive map data along with sensor fusion, which enabled them to perform advanced object classification. This classification fed their reactive route planner which allowed them to make decisions about how to cope with obstacles. (e.g. speed thru, slowly crawl over, avoid, etc...) All this functionality placed them 8th after QID.

"Mechanically Focused"

The teams that placed their focus on developing advanced mechanical platforms or intrinsic mobility to overcome obstacles seemed to fall victim to similar pitfalls.

Team Terrahawk was an extremely impressive articulated 6x6 vehicle with an independent dynamic pneumatic suspension. It had arguably the most complex suspension in the competition, allowing them to navigate from dry lake beds to the rockiest of desert terrains at speeds averaging 25 mph. Sadly, although they qualified 13th, it was this complexity that was its undoing when they were forced to withdraw prior to start due to mechanical difficulties.

Figure 2: Terrahawk at QID

Team CajunBot spent the majority of their time developing drive-by-wire control for a 6-wheeled amphibious all-terrain vehicle. For navigation they implemented a way-point following system with obstacle avoidance. This basic approach landed them 7th place at the start line.

Rover Systems fielded a custom low-profile dual-Ackerman system. Like CajunBot, they used basic way-point following with obstacle avoidance for their navigation system. This was not sufficient to qualify.

"Media Darlings"

From a technical standpoint these teams were the most frustrating. They failed to show an autonomous capability of merit yet still managed to qualify, assumedly, because the press loved them.

Palos Verdes High School Road Warrior's had as their primary interface to the environment was a SICK LADAR used for obstacle detection and a GPS system for waypoint navigation. Neither of which was ever fully implemented.

The Blue Team showed the world that creativity alone would not spawn a vehicle capable of intelligent, or even stable, control. Their platform was designed to be a self-stabilizing dirt bike for "superior off-road mobility." Unfortunately, the vehicle couldn't move more than ten feet before falling over. This made it impossible to determine what level of advanced autonomy was present, if any.

"Garage Teams"

Teams in this category spent a lot of time just trying to get their platforms running. Very little high-level functionality was displayed because the low-level basics were so problematic.

For example, Team Phantasm had a novel approach to locomotion. They replaced the tires on their ATV platform with a track-package in the hopes of increasing intrinsic mobility. Unfortunately this package plagued them with so many difficulties they never finished QID and failed to qualify for the event.

Other teams that fell into this group were; Team LoGHIQ, AI Motorvators, and The Spirit of Las Vegas.

"No Show"

We can't really say much about these teams. One never even attempted QID although the vehicle *looked* competent. The other didn't even show up to either event.

Team CyberRider fielded a really impressive looking vehicle. It had all the key components of a "Dark Horse" but never made it to the start line.

Rob Meyer Productions' vehicle never made it to the event.

GO!

And they're off

At both QID and the starting line on event day, many things happened that didn't make it into the final reports. Here's a synopsis of the collected observations from those that were there;

The Red Team came out under the banner of 5 skywriters cheering them on. They put great emphasis on their start time due, in no small part, to the number of sponsors they had present to witness their qualification (no other team had such an impressive entourage). They were the only team to qualify with less than three runs as well as being the only team to qualify on their first run. They ignored the recommend segment speed limits, in an attempt to secure the fastest qualification run. Although both of their runs were considered successful for qualification, neither was without incident (minor obstacle collisions). This was glimpse of things to come. On event day, as they made their 7 mile journey, they would impact multiple obstacles which would lead to their eventual disqualification.

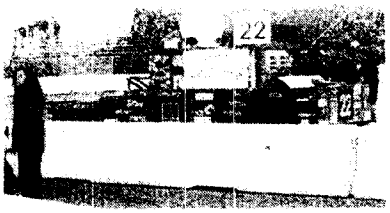

Figure 3: The Red Team in the chute

SciAutonics II was slow to start, but they seemed to build on the successes of their previous runs. It appeared that the previous run's data was either manually or autonomously optimized before the next attempt. Each time they would speed to the location of their latest run, and then slowly crawl as they explored their new frontier. On event day, they buffered some of the waypoints that were perceived as difficult, according to their previously acquired map data. This ended up being their undoing, when they attempted to reduce the risk of slipping off a cliff (using massaged waypoints) and instead high-centered the vehicle on a berm.

Team CalTech had problems at QID with the integration of their arbitrator and sensory inputs. One of the resulting problems was the false detection of an obstacle causing the arbitrator to shift gears from 1st to reverse and then back again in an endless cycle. This was eventually resolved by disabling every gear but 1st. This came back to haunt them on the day of the event when they became bound up in barbed wire and could not reverse.

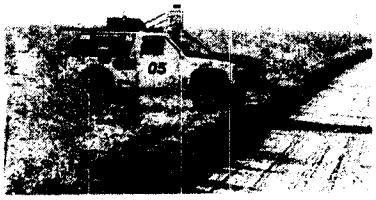

Figure 4: Team CalTech in a fence

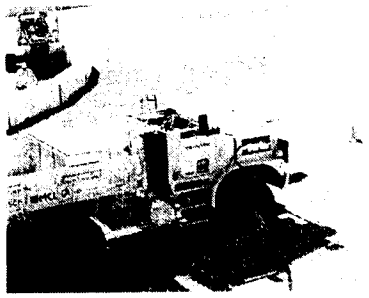
Figure 5: TerraMax at QID

TerraMax probably outweighed every other vehicle in the competition by no less than 200%. The team felt that its large size would give them intrinsic advantages over the smaller vehicles. This was not the case. In fact, their size caused more problems than it solved. Due to its large size they were given imposed regulations by DARPA specific for their team with respects to speed and start position. Another problem TerraMax had was an over-sensitivity to its size. Due to the fear that it could crush most obstacles, they seemed to give undo heed to sensor data causing it to avoid more perceived obstacles than most competitors. Finally, the problem that probably cost them the event was in way-point navigation. They had difficulty achieving way-points since they were not set with vehicles of this size in mind. In order to pass a waypoint a vehicle needs to get within a certain distance from it. TerraMax could not get close enough to some waypoints because of its immense size so it would just circle around and never progress further. On game day, they traversed until they encountered a combination of both these problems (a way-point embedded in fencing). They stopped and never resumed.

Team CIMAR was never able to integrate their 3D terrain mapping. Their best qualification run was done without the aid of their IMU. These shortcomings in integration limited their ability to circumvent obstacles to such a degree they ended up failing on event day when they got caught up in a fence and could not break free.

Digital Auto Drive (DAD) had a proprietary vision system developed for 45mph on road driving. It had a field of view that was 20feet ahead of the vehicle. This worked great when the vehicle was cruising along, but fell short for lower speeds and stop-n-go maneuvering. Also, the vehicle didn't have any sensor information for the sides or rear of the vehicle so turns were done blindly. DAD also had problems with the integration of throttle and GPS. This was costly on the day of the challenge, when the vehicle was stopped to allow a removal crew past to recover the Red Team. DAD never resumed due to wheel blockage (a football-sized rock) and a throttling problem. This was a real bone of contention for DAD because, although competitors were told they could be stopped and resumed at any time throughout the event, had they been stopped a bit earlier or later they felt they would have surpassed this point.

The Golem Group had a lot of sensor and mapping systems, but disabled them all, with the possible exception of LADAR for obstacle detection, during QID. This likely carried over to event day. They also had a shortcoming in their throttle regulation design. They appeared to be missing speed feedback; which left them

stopped on the road in gear with engine running, but without enough throttle to climb the first major hill.

SciAutonics I had more sensor feedback than their processing system could handle. They ended up removing two SICK LADARS and disabling a third. They never had a clean or complete qualification run, which translated into a runaway the day of the event, when they left the course and headed out into the desert.

Virginia Tech had a sign-error in their initial Route Definition Data File (RDDF) which resulted in them reversing out of the chute at during their first qualification run. They never implemented mapping like they intended; using their terrain mapping LADAR. Finally, a breaking problem that originated in QID cost them the competition when their brakes locked up in the start area leaving the vehicle disabled in a cloud of smoke.

Axion Racing burnt out their original transmission trying to move through an obstacle at QID. They had a new transmission installed which caused some integration issues regarding tuning parameters. After the incident, all of their following runs were at a dramatically reduced speed. Finally, the day of the event, they left the chute and performed a figure-8 conveniently right in front of the press-stand before they stopped and were disabled.

Team ENSCO was the first team to leave the chute and travel a significant distance at QID. Unfortunately upon reaching the high-speed section of the qualification course they had a stability issue stemming from a conflict between the inertial-navigation and GPS systems that resulted in the vehicle flipping end-over-end. This ensuing runs were never quite the same since the wreck took out the majority of their proximity sensors and damaged other key components. This culminated in their final flipping the day of the challenge only a quarter-mile out the gate.

Team Terrahawk had problems with their generator system. They were constantly concerned with it overheating or burning out their systems, because it wasn't integrated and ran constantly regardless of vehicle state. Another problem they had was with the way they stabilized their primary camera sensory suite by dynamically adjusting their suspension. This made the vehicle extremely jerky and frantic even on the smoothest of road conditions. They attempted to dampen this but were never quite successful. This may be why the dropped out of the Challenge moments before their start time.

CajunBot has the distinction of not only being the first vehicle to attempt qualification, but it was also the first vehicle to run out of control and hit the safety straps in the starting chute and move the jersey-barriers. CajunBot was one of the few vehicles to use more than one GPS system. This was so they could get heading without moving, as well as, to have the extra security redundancy provides. They were never able to get their obstacle detection and avoidance down pat. At QID they hit a large van multiple times and at the challenge they disqualified on a wall.

Rover Systems did not have a digital compass. They got their heading via GPS which requires initial movement. It would back up when lost, but didn't have any rear-facing sensors so it was completely dependent on previously acquired data and internal controls. They were one of the few teams, aside from Terrahawk, that were built from the ground up and actually able to compete at QID. They had dual-Ackerman steering but the vehicle control seemed under damped because it would constantly oscillate (snake-like) from waypoint to waypoint.

Palos Verdes High School Road Warrior had the greatest difficulty implementing the required Omnitech E-stop system. For most of QID they had a very complex start-up procedure until they finally fixed the implantation at the end. They have the distinction of being the only vehicle that disabled itself. During one of their runs they ground up against an obstacle and triggered their own E-stop. They were afforded more QID runs than any other team. This eventually led to them completing half the course by making trial-and-error adjustments to their steering thresholds. Finally, the day of the event, the vehicle had the most violent crash by far – flying out of the chutes, making a hard left, and slamming into the bounding barriers, displacing them by a foot, and disqualifying the team.

Blue Team, the motor-cycle platform, needed to achieve a minimum speed before the stabilization system could function. Even then, they could not tele-op more than 10 feet without falling over, let alone show signs of autonomy. They never had a run of merit at either QID or the event.

Team Phantasm was somewhat of a mystery. They had tele-op capability limited to rudimentary throttle control. After multiple qualification attempts, they never left the chute. They had RADAR and GPS mounted to the vehicle, but it was never tested at the event. Finally, their vehicle level control was all open loop.

Team LoGHIQ was one of the few, if only, true electric drive systems. They were using a LADAR with a 15° field of view that they never implemented. They would have run with RADAR and GPS but they burnt out their drive motors do to an under-specification issue.

AI Motorvators blew their transmission the first time they started to leave the chute. This was unfortunate since they waited till the end of QID to make the attempt, and therefore didn't have time to try again.

The Spirit of Las Vegas had compass/GPS errors and collided with the barrier protecting the press-box twice. Needless to say, they never ran at the Challenge.

Omnitech was charged with developing the E-Stop system which was meant to keep the vehicles safe. This

system allowed for wireless starting, stopping, and disabling of the robots. One of the biggest problems Omnitech faced was system integration. They offered to help the teams with this well in advance of the race, but few teams took them up on it. It wasn't until QID that the majority of teams tried to implement their system and this caused a lot of frustration for the finite number of Omnitech people available. Worse, it wasted a lot of qualification time, doing system level debug that should have been done before the vehicles got to QID. A typical result of this can be seen in the CajunBot false start example. Teams tried to run the system off of unregulated power supplies. As their batteries depleted, the voltage would drop below what the E-stop system required. This would result initially in deteriorated communications, and finally end in failure. In the case of CajunBot, the West Tower (located farthest from the start line) was not receiving the vehicles correct state (caused by deteriorated communications) and tried to adjust, which resulted in the premature launching the vehicle. Finally, teams complained that there was a four second latency in commands issued form the E-Stop terminals, before the robots receiver would respond.

Or were they

"Today was a most important first step in a long journey," said Dr. Anthony Tether, Director of DARPA. "Although none of the vehicles completed the course, and we were not able to award the cash prize, we learned a tremendous amount today about autonomous ground vehicle technology. Some vehicles made it seven miles, some made only one mile, but they all made it to the Challenge, and that in itself is a remarkable accomplishment."

Here are the unofficial results as well as a description of the performance of the vehicles. The following list contains the Team Name, Vehicle Number, Miles Traveled (if applicable), and summary of any relevant events.

- **Red Team** (Vehicle 22)
  Miles traveled 7.4
  The vehicle went off course and hit a minor obstacle and lost a sensor. It continued on and hit a much larger obstacle, this cause mechanical failure which resulted in the rubber on a front wheel to catch fire, thus disabling the bot.

- **SciAutonics II** (Vehicle 21)
  Miles traveled 6.7
  The vehicle went into an embankment and became stuck. It never recovered and was disabled.

- **Digital Auto Drive** (Vehicle 7)
  Miles traveled 6.0
  The vehicle was paused to allow a wrecker to get through. Later, when it was allowed to resume, it was unable to continue due to positioning and throttling issues.

- **The Golem Group** (Vehicle 9)
  Miles traveled 5.2
  The vehicle stopped. It had a throttle problem while going up a hill. After trying for 50 minutes, the vehicle was disabled.

- **Team Caltech** (Vehicle 5)
  Miles traveled 1.3
  The vehicle went through a fence, and couldn't come back through. It never recovered and was disabled.

- **Team TerraMax** (Vehicle 20)
  Miles traveled 1.2
  The vehicle started backing up and after .5 miles and was disabled. This was the only vehicle to make use of a reverse gear. This seemed to hurt it as often as it saved it in QID.

- **SciAutonics I** (Vehicle 17)
  Miles traveled 0.75
  The vehicle went off the route. After sensors tried unsuccessfully for 90 minutes to reacquire the route, without any movement, the vehicle was disabled.

- **Team CIMAR** (Vehicle 4)
  Miles traveled 0.45
  The vehicle ran into some wire and got totally wrapped up in it. It never recovered and was disabled.

- **Virginia Tech** (Vehicle 25)
  The vehicle's brakes locked up in the start area and smoked horribly. It never recovered and was disabled.

- **Team CajunBot** (Vehicle 23)
  The vehicle circled the wrong way in the start area. It never recovered and was disabled.

- **Axion Racing** (Vehicle 2)
  The vehicle brushed a wall on its way out of the chute. It never recovered and was disabled.

- **Team ENSCO** (Vehicle 13)
  The vehicle flipped in the start area (just as it did in QID) which resulted in a fuel leak. The team needed to shut off the fuel leading to the vehicle being removed from the course.

- **Palos Verdes H.S. Road Warriors** (Vehicle 10)
  The vehicle hit a wall in the start area and was removed from the course.

- **Team TerraHawk** (Vehicle 15)
  The vehicle was withdrawn prior to start.

- **The Blue Team** (Vehicle 16)
  The vehicle was withdrawn prior to start.

CONCLUSION

"DARPA's Grand Challenge proves to be too grand"
- The Register, 13th March 2004

"all the high hopes were dashed"
- TechNewsWorld, 8th May, 2004

Despite the unfavorable light many reporting agencies have cast on the event, the Grand Challenge was a very successful endeavor. First and foremost, it has put autonomous vehicles into perspective – showing people just where we are in the state-of-the-art. Many people, including those on the event teams, dramatically underestimated the difficulties with which the unmanned community has been struggling for years. A new found respect for the unmanned challenge has been given.

Second, a huge amount of experience was acquired by all those involved. There was a lot of commonality as well as some individual leaps in understanding that can contribute to the unmanned systems society greatly. Some of the most notable were:

- Intrinsic mobility is not a substitute for vehicle intelligence. It can ease the burden on intelligence, but fundamentally the need for vehicle intelligence greatly outweighs any intrinsic solution.
- Too much sensor data is just as bad as too little. Determine what is needed and match the processing power accordingly.
- The time required to do integration in the field is exponentially greater than that required doing the same integration in the lab.
- A novel solution to a common problem that doesn't add functionality or performance is just wasted design time.
- Loosening requirements to solve a problem didn't put a man on the moon. Not everybody gets to be an astronaut and we're all better for it.

This was first time anything like this was ever done. And like so many similar events throughout history, it had a challenging start. Edison went through thousands of designs before he developed a carbon filament light bulb that glowed continuously for 40 hours. The Wright brothers had several failed attempts before making history on December 17, 1903. Many years from now will people look back at the Grand Challenge with the same regard?

ACKNOWLEDGMENTS

Bruce Brendle, Michael Del Rose, Bernard Theisen, Bob La Police – US ARMY TARDEC

REFERENCES

1. http://www.darpa.mil/grandchallenge/

CONTACT

Robert T. Kania
Autonomous Navigation Team
U.S. Army TARDEC
6501 E. Eleven Mile, Building 200C
AMSRD-TAR-R/M.S. 264
Warren, MI 48397-5000
phone: 586-574-5696
fax: 586-574-8684

Philip Frederick
Autonomous Navigation Team
U.S. Army TARDEC
6501 E. Eleven Mile, Building 200C
AMSRD-TAR-R/M.S. 264
Warren, MI 48397-5000
phone: 586-574-8989
fax: 586-574-8684

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AI	Artificial Intelligence
ATV	All Terrain Vehicle
CMU	Carnegie Mellon University
COTS	Commercial Off The Shelf
DARPA	Defense Advanced Research Program Administration
DOD	Department Of Defense
DSP	Digital Signal Processing
DTED	Digital Terrain Elevation Database
GPS	Global Positioning System
IMU	Inertial Measuring Unit
INS	Inertial Navigation System
LADAR	Laser Detection and Ranging
PKS	Planning Element Knowledge Store
PSD	Path Segment Driver
QID	Qualification, Inspection, and Demonstration
RADAR	Radio Detection and Ranging
RDDF	Route Definition Data File
RDECOM	Research Development and Engineering Command
TARDEC	Tank Automotive-Armaments Research Development and Engineering Center
VETRONICS	Vehicle Electronics