

External View of the DARPA Grand Challenge

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ABSTRACT

The 2005 DARPA Grand Challenge was a “Huge Leap Forward for Robotics R&D” according to the DARPA Grand Challenge tracking website. Similar to the transatlantic flight competition that spurred commercial flights all over the world, the Grand Challenge was a step forward in the area of navigation for unmanned ground vehicles. However, questions like ‘What are the important technologies brought forth by the Grand Challenge?’ and ‘How can these technologies can assist our soldiers in the field?’ should be addressed. This paper will look at the 2005 DARPA Grand Challenge from the perspective of individuals involved in some of the Army’s unmanned ground vehicle programs. Information will be presented contrasting this year’s competition to the one held in 2004. Details of the enabling technologies from many of the competitors will be discussed along with problems they encountered at the National Qualification Event (NQE) and on Race Day. Finally, thoughts will be presented on how these technologies may be harvested in commercial and DOD R&D, current, and future systems.

1. INTRODUCTION - BOB

The original Grand Challenge took place in the spring of 2004. It consisted of two events -- a week long event known as Qualification, Inspection, and Demonstration (QID), followed by the race itself.

QID

QID took place from March 8th thru the 12th at California Motor Speedway (Fontana, California). The purpose of QID can almost be inferred from the name. The competitors basically had two hurdles to cross.

First, they needed prove to the judging staff that their vehicles were capable of competing in the event. Prior to QID DARPA officials narrowed down the list of competitors from over 100 hopefuls to 22. They did this initially by reviewing technical proposals and videos. This was further refined with follow-up site-visits. All of this lead to what DARPA intended as a shakedown before the actual event. Think of it like the time trials before a NASCAR race. This was done by running in a scaled-down version or the course mocked up at the California Motor Speedway. The course was meant to simulate the various challenges the vehicles would have to overcome on race day; there was switchbacks, waypoints obscured by obstacles (A disabled van placed directly on top of one point), an underpass (to simulate a GPS outage), a High Speed corridor, and a moving wall (to test dynamic obstacle avoidance), to name a few.

Second, and more importantly, they needed to prove their vehicle could operate in a safe and controlled fashion. This would seem almost intuitive. But given the diverse backgrounds of all the competitors (from a few friends in their garage to universities partnered with industry), the varying sizes of vehicles (from the small custom-built by Ensco to the massive Oshkosh-based by TerraMax), and the intended speeds; DARPA needed to regulate safety as carefully as possible. To this end, they employed an outside firm to develop an emergency-stop system that would be integrated into every competitor in an attempt to standardize this fundamental aspect of control. Although this standardization was wrought with difficulties, by the end of QID DARPA announced that the majority of teams were eligible to compete on race day.

Race Day

As you probably already well aware, there was no winner declared in the first Grand Challenge. In fact, only a few teams were able to breach the 5-mile mark of the XXX mile track. Carnegie Mellon’s Red Team being the most notoriabile. Even though event, as a race, may have been seen as disappointing, with no real winner. When looked at as

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an engineering experiment, it was a tremendous success. In DARPA's own words: "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."

1.2. The Second Grand Challenge

So what changed in the year and a half between the two challenges? The second Grand Challenge took place in the fall of 2005. It, too, consisted of two events – the week long precursor event formerly known as Qualification, Inspection, and Demonstration (QID) was renamed the National Qualification Event (NQE), which was again followed by the race itself.

NQE

NQE took place from September 27th thru October 5th, again, at the California Motor Speedway. The purpose of NQE still focused on proving that the teams had the potential capability to successfully complete the race and that they could do so in a safe manner. So what were the changes made from the original QID?

One change was in the implementation of the DARPA mandated safety systems. Because the fundamentals had already been put in place by the prior event, the majority of the bugs were already worked out of the hardware as well as the removal of many of the kinks in the logistics. What this meant was the teams had a much better understanding of what was required of them. They were provided with the hardware a lot sooner which allowed for a smoother integration. And the overall systems testing was done well in advance, so the majority of teams were good to go at the very onset of the NQE. This was quite different from the previous QID where safety systems issues plagued many teams throughout the entire week. What this meant was that the teams could focus on qualifying for the event rather than just passing a safety inspection.

Some other changes were in the makeup of the trial-course, itself. The first, and most obvious addition, was a XXX' tunnel placed very near the beginning of the test course. Where the previous years QID had an underpass intended to hamper GPS reception; this years NQE had a sufficiently long tunnel to guarantee an outage. The competition's designers were obviously placing a greater weight on a vehicles ability to handle the loss of GPS data. Another change, which seems to almost oppose the previously mentioned, was in the placement of the waypoints themselves. All of the competitors polled agreed that this year's waypoints were more abundant and more beneficially placed. Instead of placing them in the direct path of obstacles (remember the van from the previous event), they were placed to lead the vehicles around them. The high-speed corridor that was lined with cars was almost trivialized by the judicious placement of waypoints. Indeed, the generous placement of the waypoints actually downplayed the need for more advanced levels of obstacle detection and path planning. This, coupled with the addition of the tunnel, sends an interesting message – the vehicles should be able to deal with GPS loss but also should rely on those waypoints for safe path planning.

Whether it was over a years worth of experience, or beneficial modifications to the qualification course; teams that initial struggled the previous year, were shining through this go round. By the end of the week, 23 of the original 43 semi-finalists earned a place on race day.

Race Day

On October 8, 2005 in the XX, five teams completed the Grand Challenge course which was 132 miles over desert terrain; Stanford's Stanly, CMU's Sandstorm and Highlander, The Gray Team's Kat-5, and Team TerraMax's Black Pearl. Of those five, only the first four finished within the time limit mandated to qualify for the prize money. And of those four there could be only one winner. That winner was the Stanford Racing Team; claiming the \$2 million prize with the winning time of 6 hours, 53 minutes.

2. THE COMPETITORS

The competitors for the second DARPA Grand Challenge (DGC) came from a much broader base than those in the first competition. This fact was apparent by the larger showing of university and volunteer based teams. Many of the volunteer competitors were from large academia or industrial institutions. A few of participants had experience in robotics from either their educational/professional background or previous competitions; however the majority were newcomers to the field. One of these newcomers (Team Grey) ended up being one of the five to complete the course. Below is a brief description of most of the competitors at the second DGC with insight into their technical approach and details of some of the difficulties that they experienced on race day.

2.1. Those that finished

These are the teams that completed the race. They are listed in the order that they finished and include the time it took for the vehicle to finish the course. Terramax exceeded the time limit of ten hours but still finished the race.

2.1.1. Stanford – Stanley (Figure 1)

This team was lead by Sebastian Thrun, director of the Stanford Artificial Intelligence Lab, and was comprised of students, staff, and professors from multiple disciplines across the University. The primary sponsor for the team was Volkswagen who provided two throttle and brake by wire Touareg R5 SUV's for use in this competition. The two Touareg's were outfitted with identical processing and control hardware and software. One sensing module consisting of five SICK LADAR's, one RADAR, and one color camera was made modular so it could be easily transferred to either vehicle. Only one vehicle competed in the competition while the other was onsite as a backup. The LADAR's were each oriented with a different look angle to provide multiple range estimates of the terrain in front of the vehicle.

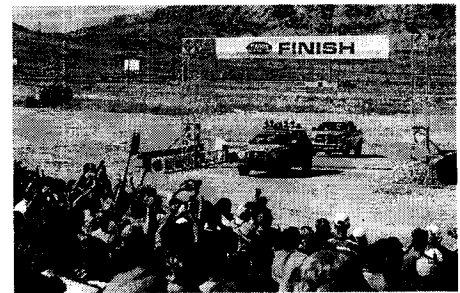


Figure 1: Stanley

The LADAR data feeds provided information about terrain 25 meters in front of the vehicle. The camera and RADAR worked in conjunction to make predictions about terrain up to 200 meters in front of the vehicle (camera providing texture consistency and the RADAR the associated coarse range). These two sets of information are used in conjunction with vehicle state estimates (UTM position, Yaw, Pitch, and Role), Route Definition Data File (RDDF) inputs, and human driver behaviors to produce a world model. The model is used to make predictions on vehicle trajectory and speed for upcoming terrain while previously made predictions are verified by the high fidelity LADAR feeds. The utilization of proven Common of the Shelf (COTS) systems allowed the team to focus on developing and extensively testing reliable intelligence and control software. Stanley had logged over a thousand hours of autonomous operation prior to arriving at the NQE. This testing time and utilization of proven COTS systems allowed the team to focus on developing and testing the control software and intelligence that enabled this vehicle to finish first in the competition.

2.1.2. Red Team and Red Team Too – Sandstorm and H1ghlander (Figure 2 & 3)

Led by William "Red" Whittaker and a team of industry and academia partners, Carnegie Mellon University's "Red Team" was one of two teams that developed two vehicles that competed in the DGC 2005. Its two entries, Sandstorm and H1ghlander, were based on a retired military HMMWV or commercial H1 Hummer platforms, respectively. Sandstorm returned from the 2004 DGC with improvements that were seen across the vehicles. Both vehicles incorporated some innovative vehicle hardware, including a custom coil-over-strut suspension, and a shock mounted electronics compartment to protect the off the shelf computing hardware. The sensor setup on the vehicles was nearly identical, differing only slightly in the mounting points on the vehicle. They included a gimbal mounted LIDAR for long range obstacle detection and avoidance, horizontally and vertically mounted SICK LIDARs for tasks such as terrain topology mapping and obstacle characterization, and GPS for global pose estimation and waypoint following. Both vehicles relied on identical computing architectures, relying on 4 Pentium III PC104 stacks for long range LIDAR control and 7 Pentium M processors for short range LIDAR analysis and drive-by-wire interfaces.



Figure 2: Sandstorm

This common architecture between the two vehicles allowed the Red Team to easily apply different strategies to both vehicles, greatly increasing the probability that one of the vehicles would complete the race. This preplanning process relied upon a tiered speed setting, a priori terrain data, and a path detailing process which allowed the Red Team to optimize the vehicles for their assumed conditions. Each vehicle had various tiers that based the vehicle speed upon the type of expected terrain and curvature for that section of the course. The expected terrain relied upon the a priori map data that was provided by the USGS and other sources. The curvature of the route was shaped by the Red Team's path detailing process, which optimized the path of the vehicle for speed while maintaining the vehicle within the corridor set by the race rules. On race morning, the team set H1ghlander as the "hare", with a more aggressive speed tier and Sandstorm as the "tortoise", with a less aggressive pace.



Figure 3: H1ghlander

During the race, Sandstorm encountered conditions which enabled the Red Team to discover a flaw in their terrain evaluation software. The software was designed to ignore LIDAR returns within a $\frac{1}{2}$ vehicle width. While the rationale for this design is not stated, it became problematic when Sandstorm was navigating through tunnels. The walls of the tunnels were ignored by the LIDAR, and this could have resulted in a collision with the tunnel. Fortunately, Sandstorm was able to detect a portion of the clear path in the tunnel, and navigate through it safely. When traversing Beer Bottle Pass, Sandstorm also grazed a rock outcropping on the wall of the canyon. The Red Team believes that a portion of the roadway was incorrectly evaluated as a hazard, forcing the lowest cost path very near the wall. This collision did not result in any damage to the vehicle, and Sandstorm completed the race in 7 hours, 4 minutes, finishing second overall.

New to the 2005 race was H1ghlander, which was equipped with a nearly identical sensor suite as Sandstorm. H1ghlander was the first vehicle out of the gate at the 2005 DGC, and was a clear favorite to win the race, starting from the NQE. At the NQE, event organizers modified the course by moving a tank trap during H1ghlander's run. The vehicle successfully navigated around the tank trap and completed the NQEs, earning the right to go first on race morning. During the race, H1ghlander encountered vehicle problems that can be summed up as "engine trouble". The vehicle had difficulty achieving the desired speeds throughout the race. Because the engine was not producing enough electrical power, this resulted in problems with the gimbal-based LIDAR for obstacle detection and avoidance. This "brownout" further deteriorated the performance of H1ghlander, resulting in a slower race time. Despite an exhaustive analysis of each subsystem related to vehicle control, the team was not able to determine the root cause of the problem. Despite these problems, H1ghlander was able to finish third overall, completing the course in 7 hours and 14 minutes.

2.1.3. Gray Team – Kat-5 (Figure 4)

The Gray Team's initial interest stemmed from various aircraft and maritime vessels. This gave them access to many experts in the respective fields. They brought together these experts, along with others (mechanical engineering, computer science, etc..) to field a Grand Challenge entry. They claim this combination has resulted in a lot of innovation in vehicle design, sensor development, and control software.

Their vehicle, The Gray Ghost, is a 2005 Ford Escape Hybrid. It was chosen as the base platform because of the high energy efficiency of a hybrid coupled with the ruggedness of an SUV. The intention was that this combination would allow the Gray Ghost to outmaneuver its competition on race day. Calling upon the expertise from their teammates; the Gray Team concentrates on research and development, integration, and testing of these devices.

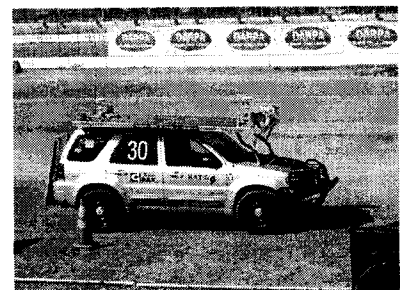


Figure 4: Kat-5

Team Gray was one of only four teams to successfully complete the 2005 DARPA Grand Challenge under the time required to claim the cash award. Team Gray finished in fourth place by completing the 131.6 mile race in 7 hours and 30 minutes with an average speed of 17.5 mph.

2.1.4. Team Terramax – The Black Pearl (Figure 5:)

The Team TerraMax members consisted of Oshkosh, Rockwell Collins, and University of Parma. Their vehicle is a Medium Tactical Vehicle Replacement (MTVR) truck platform by Oshkosh's. It weighs almost 15 tons and is about 14 feet long; by far the biggest competitor in the Grand Challenge. TerraMax was one of the five teams to complete the 132 mile race. Their time was 12 hours and 51 minutes. The sensors on the front of the vehicle consist of two Oxford GPS/INS units, a Trimble GPS unit, two Sick LMS-291 LIDARs, a IBEO Alasca LIDAR (for multiple scan lines), and three Micropix color cameras.

The path planning process was designed to direct the vehicle in the correct trajectory according to the DARPA route with respect to the sensors mentioned above. It takes in the DARPA furnished route and matches it up with the current location of the vehicle (through the GPS units). The Sick LIDAR checks for obstacles on both sides of the vehicle in case it needs to turn into the path of the LADIR scan. The IBEO LIDAR is a four plane LIDAR which is used for detecting obstacles in the front. Each of the obstacles found are matched with what the vision system sees as obstacles and a final correct obstacle list is sent to the path planner. Unlike many of the systems used for the DARPA Grand Challenge, this system uses the vision system to verify obstacles in its path, determine the terrain slope, and creates a clear path map. The clear path map uses disparity and texture to find drivable areas for the vehicle.

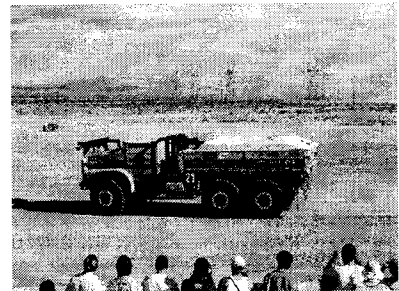


Figure 5: Black Pearl

TerraMax main challenge was its steering radius at forty five feet. The vehicle had to back up several times to align itself correctly in the first Grand Challenge held in 2004. This problem caused it to stop soon after the start by detecting something behind it and in front of it, making it continually back up and move forward until the safety judges had to power it down. To alleviate this problem for this year's race, they designed the vehicle to be both forward and rear steering. The steering radius was reduced to twenty nine feet to better align itself through tight areas, thus having a complete robotic system that could finish the course.

2.2. Those that raced but did not finish

These are the vehicles invited to the race after the NQE but were not able to complete the course.

2.2.1. Team ENSCO – Dexter (Figure 6)

This is a company sponsored team derived primarily of volunteer engineers and scientist. This was the second year for the ENSCO racing team. They competed in the 2004 DCG on race day but their vehicle ended flipping as it came around the first turn of the course. This year's team developed a more robust platform better designed to deal with the conditions of a desert race. As one of the more capable entries (in terms of sensing, processing, and mechanics), this vehicle traversed the most distance (90 miles) out of the group that did not finish. Their downfall came from behaviors that were exhibited at the NQE when the vehicle came out of the last tunnel of the race, hit a rock, and suffered a flat tire. Dexter displayed similar difficulty in dealing with the simulated tunnel at the NQE.

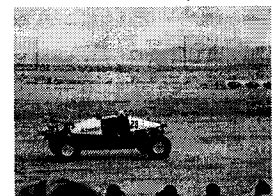


Figure 6: Dexter

2.2.2. Axion Racing – Spirit (Figure 7)

Axion Racing was a well organized, self-sponsored team of volunteers that competed in both the 2004 and 2005 DCG. The team made it to race day in 2004 but barely made it out of the start gate before experiencing navigational issues that lead to its disqualification. For the 2005 race this team appeared just as capable as any of the others to finish. They had an array of sensors and processing components that provided a high level of confidence in the vehicles autonomous capability. This was verified by the team's ability to travel 70 autonomous miles on race day before succumbing to a mechanical failure. The team's parent company Axion LLC has applied for a patent on their reactive sensory enclosure and has recently received official notification as a viable registered contractor to the US government.

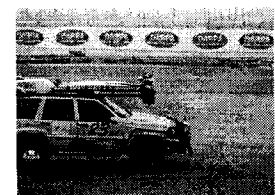


Figure 7: Spirit

2.2.3. Virginia Tech Grand Challenge Team – Cliff & Rocky (Figure 8 & 9)

Virginia Tech was one of the many university sponsored teams to enter the 2005 DCG. As a competitor in the 2004 DCG the team qualified for race day but was disqualified when it collided with a barrier and suffered a blown generator after leaving the start gate. For the 2005 competition two vehicles, with two different approaches, were entered by this team of students and faculty. One vehicle (Rocky) implemented a proactive planner, with long distance sensing, to deal with obstacles and terrain from a distance while the other vehicle (Cliff) acted in reactive mode with near-in sensor feedback. Both vehicles did well in the 2005 challenge, Rocky made it 39 miles and Cliff 44 miles, before both vehicles experienced mechanical failures, one of which was due to a malfunctioning generator.

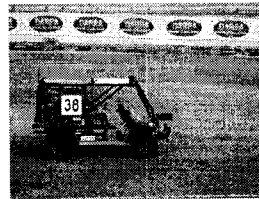


Figure 8: Cliff

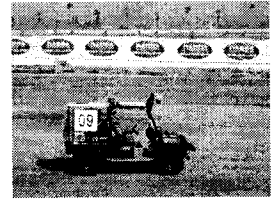


Figure 9: Rocky

2.2.4. Desert Buckeyes – Intelligent Off-road Navigator (ION) (Figure 10)

ION was an entry to the 2005 DCG from students and faculty from Ohio State University. A good portion of this team participated on the 2004 TerraMax Team developing the sensing and intelligence of that vehicle. ION was able to complete 29 autonomous miles before an undisclosed mechanical failure, attributed to a partially occluded object in the field, rendered the vehicle undrivable in autonomous or manual mode.

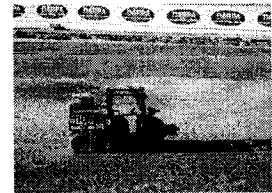


Figure 10: ION

2.2.5. Team DAD (Digital Audio Drive) – “Dad, Are We There Yet?” (Figure 11)

DAD was the surprise entry in the 2004 DCG by completing 6 miles of the course (third longest). In 2005 DAD was able to complete 26 miles of the course before their obstacle detection/terrain mapping system, spinning LADAR on top of the cab, was disabled when the power cord was disconnected as the vehicle traversed the course. The vehicle was eventually stopped due to erratic behavior.

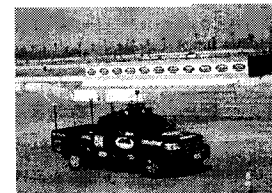


Figure 11: DAD

2.2.6. Insight Racing – Desert Rat (Figure 12)

This entry was a cooperative venture between North Carolina State University and Insight Technologies, Inc. This entry finished 26 autonomous miles with one of its primary sensors being disabled early (around the 6 mile mark) in the race before being stopped by DARPA officials. This team was invited to compete in the 2004 qualifying event but never made the trip. This was one of handful of vehicles that exhibited the behavior to be able to autonomously back-up.



Figure 12: Desert Rat

2.2.7. Mojavaton – Xboxx (Figure 13)

This was a 12 person volunteer team from Colorado. All members of the team were professionals working in different disciplines related to robotics. The team implemented a reactionary approach to completing the course. If the path was deemed impassable by one of the vehicles nine terrain sensors new virtual waypoints would be generated to avoid the unsafe area and get the vehicle back on the path. This reactionary approach allowed the vehicle to traverse 23 autonomous miles of the course.

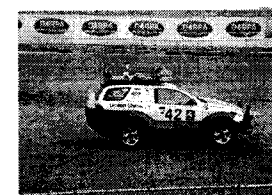


Figure 13: XBoxx

2.2.8. The Golem Group/UCLA – Golem 2 (Figure 14)

This was a joint venture between the Golem Group (independent group of engineers in Southern California) and UCLA. This team did well in the 2004 challenge with visibly older equipment, including the vehicle. The 2005 entry was a new vehicle that was moving at a good pace on race day. The team suffered a software glitch at the 22 mile mark of the race when a memory allocation error caused the vehicle to lock vehicle controls at its current state. This error sent the vehicle barreling through the high brush of the desert at 60 miles per hour before a connector fell loose on the fuse box and the engine died.



Figure 14: Golem 2

2.2.9. Team CajunBot – CajunBot (Figure 15)

Team CajunBot was comprised of a volunteer group of professors, students and staff from the University of Louisiana at Lafayette. This team also competed in the 2004 event but, like the rest of the competitors, was unable to finish the race. The 2005 entry finished 17 miles of the course before the vehicle lost an actuator when it was put into pause mode for 50 minutes to allow other competitors to pass. In pause the breaks were applied and the actuator overheated.

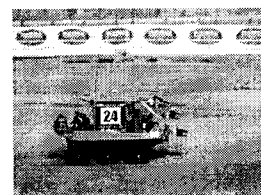


Figure 15: CajunBot

2.2.10. SciAutonics/Auburn Engineering – RASCAL (Figure 16)

This collaborative effort between SciAutonics, LLC and Auburn Engineering returned to compete in the 2005 DCG. The team's 2004 entry completed .75 miles of that course but had a computer hard drive failure that ended its run. The 2005 entry completed 16 miles before its run was terminated for an undisclosed reason.

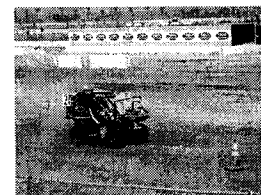


Figure 16: RASCAL

2.2.11. Intelligent Vehicle Safety Technologies I – Desert Tortoise (Figure 17)

This team was comprised of professionals with sponsorship from Ford, Delphi, Honeywell, and Perceptek. This team was perceived as a favorite from the other competitors given the equipment and support from their sponsors. Their vehicle managed 14 miles of autonomous operation before being disabled prior to potentially colliding with a power line tower. Differences between the route file provided by DARPA and the vehicles mode of operation caused the system to operate in the wrong configuration for on road traversal which made the vehicle appear unstable.



Figure 17: Desert Tortoise

2.2.12. CIMAR – NaviGATOR (Figure 18)

This was a collaboration of graduate students and faculty from the University of Florida and Autonomous Solution Inc. This team also competed in the 2004 DCG managing to travel one mile under autonomous control. This year the team developed a new custom platform and completed 14 miles of autonomous traversal before being eliminated from the race. The custom vehicle was designed for off road navigation, based on the teams experience from the last race, and had control issues when required to go at high speeds on paved surfaces. They also noticed the vehicle had a tendency to drift right when using color camera's for road detection. The combination of these situations caused the vehicle to eventually veer off the road, recover, overshoot and be disabled before potentially colliding with a phone pole.

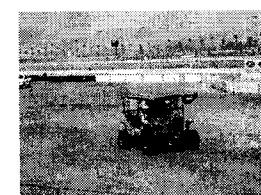


Figure 18: NaviGATOR

2.2.13. Princeton University – Prospect 11 (Figure #19)

This was a primarily undergraduate group of students who received senior thesis and independent study credits for working on this project. The effort was completely funded by unrestricted gifts to the university and proceeds from the universities endowment. The team was comprised of 37 undergraduate students and a few graduate student advisors. The team finished 10 autonomous miles before being disabled due to a memory leak, causing a frame rate calculation error which resulted in the vehicle behaving erratically. This was the only vehicle to compete at the competition that used pure vision as its only sensory input for terrain and obstacle detection.



Figure 19: Prospect 11

2.2.14. Team Cornell – Spider (Figure 20)

This is a team of students and faculty from Cornell who have competed in other robotic competitions (e.g. Robocup, unmanned underwater navigation, etc...) in the past. The team had an objective of simplifying the complexity of the autonomous vehicle by utilizing a robust high mobility platform. The sensing was LADAR based and the vehicle was able to complete 9 autonomous miles of the race.

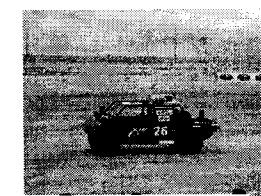


Figure 20: Spider

2.2.15. Team Caltech – Alice (Figure 21)

This is another team of primarily undergraduate students. The team also competed in the 2004 challenge but with an older vehicle. The new vehicle was a robust 4-wheel drive off road vehicle. The team completed 8 autonomous miles before an error in the vehicles positioning system, along with the failure of two medium range terrain sensors (SICK LADARs) caused the vehicle to run off the road and crash into/over barriers right in front of the media section of the course.

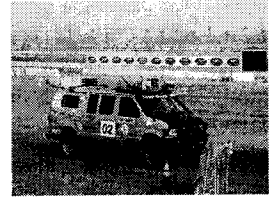


Figure 21: Alice

2.2.16. MonsterMoto – JackBot (Figure 22)

This team was comprised of essentially two primary team members. The teams engineering approach was to keep the vehicle design simple in hopes that it would be better prepared to cross the rough desert terrain. This approach enabled the vehicle to complete 7 miles of the competition.

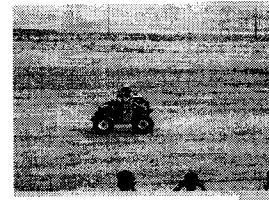


Figure 22: Jackbot

2.2.17. The MITRE Meteorites – The Meteor (Figure 23)

This was a team of engineering professionals working in the fields of robotics, signal processing, software and systems. The MITRE Corporation was the primary sponsor for this team. Their vehicle design was based on the concept of keeping things simple and focusing on the skills they had while farming other work out. The vehicle traversed a mile of the course before being eliminated from the race.

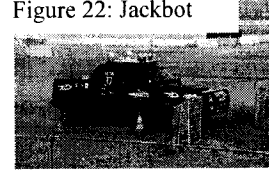


Figure 23: Meteor

2.3. Those that did not qualify

The rest of the field consisted of teams that did not qualify for race day according to DARPA selected criteria for displayed capability at the NQE. At the NQE, 27 teams were able to successfully complete the course but DARPA had earlier determined that only 23 could be invited to the race. Other than the four teams that finished the NQE but were not invited to the race, the vast majority of the remaining teams fell victim to underestimating the complexity, time, and required resources to effectively put an autonomous ground vehicle together. Much less a autonomous vehicle that would be able to traverse a 150 mile desert trail or consistently display the capacity to do so. This could be attributed to a majority of these teams being new to the competition and not having the previous experience afforded to those who competed in 2004.

3. THE AFTERMATH

Now the question arises as to what was really accomplished by this race and where do we go from here. It is still early to see the true effects that the DCG may have on the field of autonomous ground vehicles but there is some preliminary results that deserve mentioning. However, to understand the relevance of some of these early results it is important to first understand the relevance of the competition.

3.1. What was accomplished?

The question is how relevant was the work performed at this competition? This is really a set of questions that must be addressed individually. We will break this question down into the following categories:

3.1.1. The Challenge:

It is understood that the challenge was to autonomously traverse approximately 150 miles of desert terrain in ten hours or less with no human intervention. However, what was the level of autonomy required to accomplish this task? The terrain of the DCG II was described by Red Whitaker (Red Team Lead) as a two in terms of difficulty to traverse on a ten point scale. This definition was specific to how difficult it would be for a human to traverse the terrain in the vehicle. Sebastian Thrun (Stanford Team Lead) had similar notions about the terrain. This raises questions as to why the course might be described in such a manner.

So how difficult was the terrain? This question could be restated as how much information was required to be sensed and reacted upon compared to how much was inherent in the task? DARPA provided each team with a Route Definition Data File (RDDF) that contained the path the vehicle should traverse, associated corridors of deviation for each waypoint, as well as associated speed for each waypoint. The speed tags on each waypoint would ramp the vehicles up and down in speed when the vehicles approached different types of terrain (e.g. slower around corners and

faster on straight roads). Also the frequency of waypoints would increase when approaching more difficult terrain. Finally, no real obstacles appeared on the course that were intended to be in direct conflict with the vehicles path. The obstacles that were part of the course were native to the urbanization of the surrounding area around the desert (telephone and power support structures, over passes for highways, etc...).

Thus, it can be derived from the above information that this was not a full blown open dessert race but rather a well planned and manicured one. The terrain could generally be described as paved and unpaved roads with burms of dirt on the sides of the unpaved roads. These burms of dirt are significant because any terrain sensing system would recognize the change in elevation created by these burms and help the vehicle define the roads. Also, the desert trails were well saturated with water in order to decrease the potential of dust affecting the vehicles sensing capability, either through storms or vehicle created dust. All of this information is not presented to demean the value of the race but rather to point out the facts to the interested observer. It can thus be concluded that the terrain was relatively benign in regards to what you might expect from a dessert race and the required level of autonomy to traverse this terrain must be consider less extensive for this reason. A proper definition for the autonomy required for this race would be Assisted Autonomy (AA). This term is appropriate because this race was not a true measure of the autonomy of the vehicles, but rather a measure of what is possible given the correct circumstances (with DARPA serving as the assistant in determining this).

3.1.2. Technology advancements:

Was there any new approach to ground autonomy that can be derived from this competition? Again this is a multipart question that should be addressed separately.

3.1.2.1. Mechanically:

Considerable innovation was attempted in this arena. Many teams worked under the assumption that providing a robust high mobility platform would allow the vehicle to be less reliant on its perception and intelligence. This thought actually back fired on most of these teams as they experienced mechanical failures either during the NQE or the actual race day which disabled their vehicle from completing the course. Below are some of the mechanical advancements implemented by a few teams:

- AI Motorvators – Custom off-road chassis
- Team Jefferson – Custom off-road chassis
- Team Ensco – Custom off-road chassis
- Team CIMAR – Custom off-road chassis
- Axion Racing – Reactive Sensory Enclosure (RSE)
- Blue Team – Motorcycle Chassis
- CyberRider – Custom off-road chassis
- Terra Engineering – Custom off-road chassis

Team Ensco, Team CIMAR, Axion Racing were the only teams in this group to qualify for race.

3.1.2.2. Computationally:

This section is broken down into hardware and software.

3.1.2.2.1. Hardware:

Many of the teams went with multiple Common off the Shelf (COTS) Pentium enabled computers. Almost all teams utilized Linux as the processing environment of choice. The few teams utilizing vision would normally have a windows interface to those commercial components. One of the more impressive utilizations of hardware was accomplished by Team DAD. Similar to the first competition, their architecture funnels data directly from the sensing component (3D LADAR) to DSP chips that are over-clocked and able to process the information with amazing efficiency. This allows them to deal with a large amount of information in short periods of time, which is desired when collecting terrain information while moving at high speeds.

3.1.2.2.2. Software Architecture:

Almost all of the teams developed their own software to interface to their sensing modules as well as developing their own architecture for processing this information. Given that every team had a unique way of distributing and

processing information, the only measure of advancement would be detailed by the results of their run. The most impressive approach was demonstrated by Stanford with their emphasis on probabilistic graphical models, machine learning and state estimation control software.

3.1.2.3. Sensing:

Most teams implemented COTS sensing modules on their platform. The most popular sensor was the different variants of the SICK LADAR. This could be attributed to the relatively low cost of the sensor, availability of interface documentation and algorithms, and effectiveness of LADAR versus other active (RADAR, SONAR, etc...) and passive (daylight camera, IR, etc...) sensors. Princeton and the Blue Team were the only two entities to go with a primary sensing solution that was not LADAR based (both using stereo paired daylight camera's). Other LADAR's used at the competition include the Riegl COTS system and custom built systems from Team DAD and Red Team. The DAD system was of particular interest because it was able to map the terrain 360 degrees around the vehicle at high fidelity.

3.1.2.4. Technology advancement summary

As to be expected from a competition with this type of end product and imposed time frame, ingenuity was limited by near-term feasibility. Your chances of success were much higher going with a proven technology rather than striving for unique capability. As the results of the race have shown, the more successful teams were those that tended toward proven technologies for sensing, mobility, and computing while focusing on developing reliable and well tested control software. Thus, ingenuity in design was not a major by product of this competition.

3.1.3. Life after the competition

This is the area that most embodies what was really accomplished by the competition. The DCG brought large scale ground robotics into the consciousness of general society and demonstrated that these systems are feasible and near-term capable to accomplish select missions in controlled scenarios. The competition also accelerated the process of these near term solutions being implemented by providing a larger field of robotic expertise in which to draw from. This was accomplished in three ways:

First, a collection of small autonomous ground vehicle focused companies have been spurred by this competition (approximately a fourth of the participants have started new companies or added focus to existing companies based off their participation in this competition);

Second, a new group of engineers and scientists with experience in autonomous ground vehicles has been created as a resource for new or existing companies. Also, universities are likely to put more focus and resources towards developing engineers focused on ground robotics;

Finally, interest in ground vehicle autonomy has increased in both the DOD and private sector: A new requirement in future crop harvesting has emerged to have a large number of future harvesters autonomous, robotically assisted convoy has renewed interest from both private and government entities, multiple entities from the automotive industry are looking at incorporating levels of autonomy in future vehicles, the construction industry is investing in automating heavy loaders (and other vehicles) operating at excavation sites, the mining industry is looking into autonomous ground vehicles that monitor and explore potentially hazardous mines to determine if it is safe to send personnel in, lawn maintenance industry has increased its efforts to produce affordable autonomous mowers, security agencies are interested in autonomous vehicles that can autonomously roam, monitor, and secure sites, the shipping industry is looking into having autonomous vehicles that remove and recoat paint on ship hull's.

4. CONCLUSION

It is obvious that interest in ground robotic systems has seen an increase in recent years. This competition existing is proof to that fact. It is likely that autonomous ground vehicles will become part of everyday society at one point in the future. This competition will likely directly or indirectly have an influence as to when these systems emerge.

5. REFERENCES

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*Team technical papers and websites were utilized in the creation of this paper which can be found on the 2004 and 2005 DCG websites

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