About *Prospect Eleven*

and

Princeton University's "DARPA Project"

Background:
Prospect Eleven is the team name for Princeton University's entry in DARPA's Grand Challenge of 2005, a competition of truly autonomous vehicles traveling a prescribed course. The challenge of the "Challenge" is to "build or modify" an automobile-sized vehicle that can negotiate a prescribe course containing randomly place obstacles without any human intervention. The Challenge was originally contested in April, 2004; however, none of the entries completed the course. In fact, the most successful vehicle completed only the first seven (7) miles of the more than 150 mile course. As a result, DARPA (Defense Advanced Research Projects Administration), decided to organize a second Challenge that is to take place in October, 2005.

Princeton University did not participate in the first Challenge; however, upon learning, in May 2004, that a second Challenge would be contested, a group of undergraduates led by Ben Klaber '05 approached Professor Alain Kornhauser with a desire participate in the 2005 Challenge. In May 2004, Princeton University officially enter a vehicle named "*Prospect Eleven*" with the stipulations that it be an undergraduate student, as opposed to a professional staff, activity AND that the principle objective be that it complement to the highest degree possible the students' academic experience at Princeton. Bounded by those constraints, a multidisciplinary team of students and advising faculty volunteered to participate in the "DARPA Project".

Throughout the design, build and test process the guiding objectives have been academic relevance, simplicity, elegance and minimal expenditure of funds. Academic relevance because it is Princeton; simplicity because it is too easy to make this Challenge so hard that it is undoable, thus the need for elegance. Finally, funds were to be used only for summer stipends for participating students and the purchase of needed computing, command and control apparatus. No funds were available for students during the academic year, professional staff, and advising faculty. Student participation during the academic year had to be justifiable for academic credit or as an extra-curricular activity.

Summer of 2004:

During the summer of 2004, a team of to-be Seniors from the class of 2005 did the original ground work for *Prospect Eleven*. Ben Klaber'05 ORFE, Ben Essenberg'05 MAE, Joel Mancl'05 MAE, Trevor Brooks'05 CS, Philip Wei '05 CS, Daniel Chiou'05 ELE, Michael Pasqual '05 ELE, Each of these students went on to use their participation in the DARPA Project as an application basis for their Senior Thesis. Professor Kornhauser obtained, with the help of Rick Spina '85, a salvaged vehicle from General Motors. Trimble Navigation and ALK Technologies donated GPS receivers. Otherwise, all student summer salaries and other equipment was purchased using the endowment funds from the CSX Transportation Research Fund and the Lion Transportation Senior Thesis Fund.

2004/5 Academic Year and the 1st Site Visit:

During the 2004-05 academic year, the participating seniors were joined by several underclassmen. Bryan Cattle '07 ELE and Anand Atreya'07 ELE actively participated as part of independent research activity. Freshmen Andrew Saxe '08, Gordon Franken '08, Josh Herbach'08 and Brendan Collins'08 joined on an extra-curricular basis. The faculty advising team, led by Professor Alain Kornhauser (ORFE), included Professors Stuart Schwartz (ELE), Bradley Dickenson (ELE), Sanjeev Kulkarni (ELE), Clarance Rowley (MAE), Daniel Osherson (PSY), and Szymon Rusinkiewicz (CS).

Culmination of a year's activity took place with the original DARPA Site Visit on May 6, 2005. The purpose of the Site Visit was for DARPA to measure the progress of each of over 100 entries and select the best 40 as "Semi-Finalists". The Site Visit consisted of three (3) traversals of a prescribed 220 meter S-shaped course that contained two randomly-placed obstacles. The autonomous vehicle was required to stay within prescribed coordinates bounding the course while avoiding collisions with the obstacles. Each run was timed. Faster was better. The Site Visit took place at the West Windsor Fields where the prescribed course was properly laid out.

It was an enormous accomplishment for the *Prospect Eleven* team to, in one year, properly modifies a production vehicle that could autonomously control its throttle, brake and steering utilizing inputs from a GPS receiver, hood-mounted camera, digital compass and stock sensors such as wheel ticks and throttle settings. All was accomplished under the Princeton guidelines that it be entirely an undergraduate student project focused on academics, elegance, simplicity and the minimal use of funds.

During the Site Visit, the first run was brought to an emergency stop immediately after *Prospect Eleven* failed to avoid the first obstacle. It was unfortunate that the emergency stop was activated, because, as was subsequently learned, it was also important to determine if the vehicle would stay within the prescribed boundaries, irrespective of its ability to avoid obstacles. More points could have been earned by completing the run. During the second run, *Prospect Eleven*, successfully avoided the first obstacle "nicked" the second obstacle and completed the course in a very fast time of 56 seconds without violating the course boundaries. The third run had *Prospect Eleven* nicking the first obstacle, running right over the second and quickly completing the course once again without violating the course boundaries. Thus, the results were mixed. On the positive side, the automated throttle, brake and steering systems were well integrated with GPS, machine vision and other sensors. Unfortunately, *Prospect Eleven* had serious problems with obstacle detection and tracking which resulted in its poor performance in collision avoidance.

When the top 40 Semi-finalists were announced in early June, *Prospect Eleven* was not included; however, it did come very close. So close, that upon further consideration, DARPA decided to offer the *Prospect Eleven* team "Alternate" status.

Summer 2004, Preparing for the 2nd Site Visit:

The Alternate status provided *Prospect Eleven* a second chance. A team of seven (7) students, advised by Prof. Kornhauser, worked since May as summer research assistants, funded by the CSX Transportation Research Fund. The student research assistants, all undergraduates, were Scott Schiffres '06 MAE, Kamil Choudhury'06 CS, Bryan Cattle '07 ELE, Anand Atreya'07 ELE, Andrew Saxe '08, Gordon Franken '08, and Brendan Collins'08. These students have completely rebuilt *Prospect Eleven*. They have ruggedized the throttle, braking and steering systems, shock-mounted the computers, redid all of the wiring, developed a stereo vision system for object detection and identification and rewrote the longitudinal and lateral control functions. In pre-site visit tests, *Prospect Eleven* was able to detect objects, avoid them and stay within prescribed courses most of the time. While some problems still existed and not all bugs were out of the code; performance was promising. *Prospect Eleven* was able to successfully negotiate a 750 meter long closed course several times prior to ending with some type of computer crash. Enormous progress was made during June and July; however, reliability remained a serious issue.

The 2nd Site Visit:

The 2nd Site Visit, was scheduled for 8:00 am, Tuesday, August 16, 2005 at West Windsor Fields. Repeated will be the first Site Visit with three runs down a similar S-shaped course containing randomly placed obstacles. Links to the 1st run, 2nd run and 3rd run. An optional fourth run choreographed by the *Prospect Eleven* team will also be traversed. Practice session were run on Monday, August 15, 2005 from 8am until 6pm. Remote web viewing of the practice session and the site visit were available on the CoPilot|Live site: http://live.alk.com Use Account Name: `Prospect11` and Password: `Princeton` to monitor *Prospect Eleven*'s position every five seconds. Links to data and a video of the optional run. Prospect Eleven's superior performance earned Princeton University an invitation as vehicle #41 to the National Qualifying Event (NQE) held on September 27 through Oct 5, 2005 at California Speedway in Fontana California.

Preparation for the National Qualifying Event (NQE):

Now that Prospect Eleven had earned an invitation to qualify for the Grand Challenge it had one month in which to be prepared and tested in order to be competitive in a substantially harsher environment. Testing took place at West Windsor athletic fields, Tom Haines Berry Farm, and the JOUSTER robotic testing facility at Virginia International Raceway. During this intense period, critical and timely assistance was provided by:

- Tom Haines in allowing us full access to use his “pick your own” Berry Farm in Pemberton, NJ to test Prospect Eleven in sandy, narrow roads and paths,
- Michael McKay, Vice President for Facilities, Princeton, University, for making readily available a truck, trailer and driver to move Prospect Eleven to Pemberton, NJ and to the Virginia International Speedway for testing,
- Steven Healy, Director of Public Safety and all of the members of his department who kept a watchful eye and lent continuous support throughout the long hours of testing and refining, and
- Jeff Graydon, Associate Director for Facilities, Athletics and Gary Walters, Director of Athletics, for allowing us to test Prospect Eleven on the West Windsor athletic fields and for delaying the seeding of the new cross-country course for 10 days to allow us to have access to an ideal testing environment. This level of cooperation and assistance towards a purely academic activity by a Director of Athletics epitomizes the ideal relationship that exists at Princeton University between athletics and academics.

The National Qualifying Event (NQE):

The National Qualifying Event (NQE) was held at California Speedway in Fontana CA over eight (8) days between September 27 and October 5, 2005. The following nine (9) members of the team accompanied Professor Kornhauser at the NQE: Andrew Saxe’08, Josh Herbach’08, Brendan Collins’08, Gordon Franken’08, Bryan Cattle’09, Anand Atryea’09, Scott Schiffres’06, Kamil Choudhury’06 and Rachel Blair’06. They were joined for part of the time by three students who had graduated last June: Ben Essenber’05, Daniel Choiu’05 and Jeff Jones*05. A total of forty-three (43) “bots” participated, the original 40 plus three (3) that were selected from nine (9) alternates that completed a 2nd site visit. Princeton’s Prospect Eleven was assigned # 41. The purpose of the NQE was to select the best 20 “bots” to participate in the Grand Challenge Event (GCE).

The NQE involved the running of a 2.2 mile closed serpentine course defined by GPS waypoints with associated lateral boundary off-sets and speed limits that were to constrain the “bots. Fifty (50) “gates” marked some of the boundaries and five (5) obstacles (four (4) vehicles and a Normandy-style tank trap) were place in the “center” of the desired travel lanes. The course also included a 100 foot-long tunnel (no GPS availability), rumble strips, hay bail lined boundaries and a concrete barriers simulated some of the narrow and rough conditions that were to be expected during the Grand Challenge.

Prospect Eleven made five (5) runs of the 2.2 mile NQE course. During the course of the first two runs it became evident that Prospect Eleven's vision system was performing extremely well, but that its GPS/INU (Inertial Navigation Unit) was not precisely aligned. Even with this misalignment, Prospect Eleven completed its first run by passing through 48 of the 50gates and neatly avoiding each of the 5 obstacles. A detailed analysis of the data captured during the run indicated that Prospect Eleven had in fact negotiated a much more demanding course. In many instances the misalignment caused one of each gate's pylons to be substantially inside its feasible GPS lane boundaries; thus, substantially reducing Prospect Eleven's perceived feasible lane width ahead. In all but two instances, Prospect Eleven's stereo vision control system enabled it to stay within this narrower lane during the first run. Even with the misalignment, Prospect Eleven stood in 4th place after the first run. It was not so fortunate in the second run. The misalignment, coupled with a sluggish braking system response, cause the vehicle to slam through the left pillar of the first gate and experience a perfect elastic collision with a parked car serving as the left pillar of the second gate, thus ending a disastrous 2nd run. In both cases, we later determined that the GPS alignment was so poor that it perceived that it had no feasible lane ahead and its response to its brake command was so poor that it was not able to stop before the collisions.

Prior to the third run improvements were made to braking system's dynamic response and, suspecting bias in GPS, a offset translation was made in the GPS code. This kluge allowed Prospect Eleven to successfully traverse all 50 gates and avoid all 5 obstacles; however, it did nick a couple of the tire stacks. It was back in the top 20 but needed one more good run. That did not come in the fourth run. Barely 20% into the course, the steering controller went unstable and had to be halted as it mounted some hay bales. Upon review it was discovered that several remote processes had been left running on its vision computer. At the point of instability, these processes were consuming such a substantial portion of the processing power that the vision system was updating steering commands less than once a second. In retrospect, it was unfortunate that all the blame for this malfunction was placed on our stupidity for failing to turn off the unneeded remote processes. Had we looked more deeply, we may have uncovered the bug that proved to be Prospect Eleven's demise in the Grand Challenge. We were again out of the top 20. Knowing that we had only one more chance, we focused on and found the alignment error in the GPS. This enabled Prospect Eleven to have an essentially perfect fifth run, passing through all gates, avoiding all obstacles and tire stacks. It earned a 10th seed in the Grand Challenge Event.

One final accomplishment at California Speedway was to test the limits of the vehicle. As we were leaving for Primm, NV, we tested Prospect Eleven using one of the speedway's large parking lots. We set up a large oval to give us the opportunity to test the stability of the steering controller at high speeds. It proved to be stable on flat smooth surfaces at speeds up to 65 miles per hour.

The Grand Challenge Event (GCE):
Twenty-three (23) bots were invited to participate in the Grand Challenge Event on October 8, 2005. Prospect Eleven was seeded 10th . The event involved the traversal of 132 mile course in the desert outside Primm, Nevada. The fastest bot completing the course in under 10 hours would claim the $2 million prize. The actual coordinates of the course were not divulged to the teams until 4:00 am on October, 8; 2 hours before the start of the event. Provided was a standard file containing waypoints, lane widths and speed limits. No information was provided on lane roughness nor the location of obstacles, if any. In preparation for the receipt of this file, Josh Herbach'08 had written an analysis program that allowed us to view, modify and evaluate the course. This allowed Josh, Andrew Saxe'08 and I to modify the constraints and to estimate some of the impacts of the modification. While we had conducted one high speed test of Prospect Eleven, we were not confident about its performance at high speed. Since a 35 mph global speed limit allowed for completion in just under 9 hours, we imposed this conservative constraint. On the other hand, we were more confident in our stereo vision system than we were in the accuracy of GPS. We increased the narrowest lanes to be at least 9 feet wide, thus relying on vision to keep Prospect Eleven on the feasible path ahead.

Prospect Eleven performed admirably in the Challenge. It launched without difficulty and reappeared on schedule at the 8 mile mark and passed over the Union Pacific mainline at the 9 mile mark. Unfortunately, the steering became unstable shortly thereafter after completing about 9.4 miles. A "Personal Best". After recovery of the vehicle, it was apparent that there was a bug in the obstacle detection code that grew to consume essentially all of the computing resources. One segment of the code failed to dispose of obstacles that had been passed. By the 9th mile, the process was analyzing thousands of obstacles in its effort to determine a feasible way ahead, thus, it was back to updating the steering system less than once a second.

In the end, Volkswagen (a.k.a. Stanford) won the Challenge by finishing in just under 7 hours. Carnegie Mellon's two entries, Highlander and Sandstorm, finished 2nd and 3rd in just over 7 hours and two others, Grey Team and TerraMax completed the course in about 10 hours, but the students of Prospect Eleven were the real winners. The learning and experience were "Priceless". They knew in their hearts that they had created a phenomenal autonomous vehicle. The only disappointment was in not proving it.

Unfinished Business:
Shortly after our return to campus and the placement of Prospect Eleven on in its van "back to Nassau Hall" Bryan Cattle'08 called Wm. Culbreth, Dean of Engineering at UNLV inquiring about temporary storage for Prospect Eleven. The resulting enthusiastic offer of assistance made it clear that Prospect Eleven needed to be turned around in order to give this Prospect Eleven yet another "second chance" to prove its worth. There was unfinished business to take of and the upcoming Fall Break was the time to "Just Do It". So, on Saturday evening, October 30, 5 team members, Andrew Saxe'08, Gordon Franken'08, Bryan Cattle'07, Anand Atraye'07 and Scott Schiffres'06 and Prof. Kornhauser returned to Las Vegas. Joined by Ben Essenburg'05 on Sunday morning,

they found Prospect Eleven at the Center for Energy Research. Using the shade cast by the Amonix Integrated High Concentration Photovoltaic panel, Anand Atraye set out to find the bug in the code. In a couple of places in the code, he changed one line: "Everywhere I saw something like:

```
currentObstacles.RemoveAt(i);
```

I preceded it with:

```
State.RelativeFrameUpdated -=
currentObstacles[i].relativeFrameEventHandler;
```

The problem was that each time we removed an obstacle from the list of current obstacles, we were not unhooking it from the `RelativeFrameUpdated` event. Thus, the garbage collector never determined that the old obstacle was no longer needed, and as a result it was never cleared." In other words, Prospect Eleven never really "forgot" about an obstacle that it had seen and continued to determine if it needed to avoid it. Thus, after 9+ miles, it was still evaluating obstacles it had detected at the start. The list had grown to thousands of obstacles.

With the code change and a recalibration of the GPS/INU, we drove Prospect Eleven the 35 miles down I-15 to Primm in position for a second chance at the 2005 DARPA Grand Challenge on Monday morning.

Assault on the 2005 Grand Challenge Course. Early Monday morning, October 31, 2005, ironically Halloween, we set out to run the 2005 Grand Challenge course exactly as we did during the actual Grand Challenge. Prospect Eleven was using the same RDDF (file of GPS waypoints that define the course) and the same global constraints and control coefficients. The only substantive difference was the change in the "one line of code". Since had limited support personnel, comprising of two support vehicles, it was necessary that we have someone ride inside Prospect Eleven in case an emergency stop condition was encountered. It simply wasn't practical to monitor both the environment ahead and the stability of the vehicle entirely from the support vehicles. While possibly dangerous, Professor Kornhauser rode the entire distance behind the wheel of Prospect Eleven, prepared to instantly take over command of the steering and brakes, while in no other way interfering with its autonomous operation. While the plan was for Professor Kornhauser to be alone, Andrew Saxe was permitted to ride "shotgun" during the first stage which traversed a dry lake bed. It was expected posed few risks. Andrew's job was to toggle the "kill" switches that would enable Prof. Kornhauser to take over control of the vehicle.

Launch came at PST and was uneventful. Everything was perfect until just miles into the course when a mirage seemed to appear in the distance. Not to worry, it's the desert; however, it quickly became apparent that the "dry" lake was not so dry. It had rained since the Grand Challenge and the course was not traversable in a non-amphibious vehicle. The decision was to cease autonomous operation in order to not lose the vehicle. A precise autonomous run of the 2005 GC course was infeasible because of the rain. With the current condition, no Grand Challenge vehicle could have made it beyond this point. In fact, if this condition would have existed during the Grand Challenge, DARPA would have altered the course. It now became evident why, during the Grand Challenge, the course was not divulged earlier than 2 hours before the race. I was to ensure that the course was a fair one and that some environmental condition had not made a part of the course impassable.

Rather than go home, the decision was to continue to uncover Prospect Eleven's autonomous operational limits by continuing on the traversable portions of the 2005 GC course. The first limit had been established: it can't traverse lakes and isn't smart enough to figure out a way around them, if the "desired" course is through them. That's the first thing that was discovered that we need to work on.

After a brief diversion around the lake, autonomous operation was reinitiated at reemergence of the 2005 GC course. This incident made it apparent that two people were needed inside the vehicle to properly monitor the road ahead. Other than the lake situation (which occurred at 2 other points), the only non-autonomous diversions were due to

1. places where the "road" had been "bulldozed" probably to discourage exactly what we were trying to do. These places existed at XXXX and XXXX, and
2. on XXXX a public road, where we pulled over to let a cement truck pass us (if this situation would have occurred during the Challenge, DARPA would have paused the vehicle and instructed the cement truck to carefully pass the vehicle).

These two incidents refine the operational limits that need to be worked on. Specifically, Prospect Eleven needs the capacity to be able to violate its desired route constraints and set out to find any feasible path ahead. At present, it does not have this capability.

Also, Prospect Eleven was paused several times, much the same way that DARPA may have legitimately paused the vehicle during the Grand Challenge. Pauses were instituted prior to crossing public roads, the Union Pacific at-grade crossing, upon encountering closed gates, that once opened, were negotiated autonomously and for preparing the onboard camera to record the traverse of Beer Bottle Pass at night.

Except for the above constraints, none of which existed during the Grand Challenge, Prospect Eleven autonomously traversed the course. No changes, corrections or alterations were made to any of Prospect Eleven's autonomous systems. It can be argued that Prospect Eleven autonomously traversed an even more challenging course than that of the 2005 Grand Challenge. Except for the two lakes and the two "bulldozed" areas, Prospect Eleven was autonomous, including places where the road was significantly rougher than what existed in early October.

Prof. Alain L. Kornhauser
November 29, 2005