CHAPTER XII. RESEARCH METHODOLOGY

The foundation of much of this research is *critical scholarship*. To the extent possible, any conclusions presented by the author are supported by *objective evidence*. For the purposes of this research, objective evidence is considered to be that presented by primary public and academic sources which can be independently confirmed. These sources are referred to herein as "published records". The complete body of published records is referred to herein as "the published record".

To support objective, independent analysis, the author has attempted to separate the reputations of the universities and corporations involved from analysis where possible through the use of team numbers, in lieu of names, focus on participation in the 2004 and 2005 GCE in lieu of competition, and eliminate completely the use of informal testimony, or hearsay.

It is possible that participants in the 2004 and 2005 GCE are able to remember details and events which did not become part of the published record, and many of the teams which participated in the 2004 and 2005 GCE maintain websites providing points-of-contact through which the author could have solicited additional technical information or requested clarification of published records. However, the author determined that reliance on informal testimony or hearsay would introduce an additional element of uncertainty into what is already an uncertain record, and the decision was made early to rely on published records alone. As a result, no attempt was made to reconcile the published record with informal testimony or hearsay through email or telephone conversations with the teams.

The author does not consider manufacturer product literature to which access is directly controlled by the manufacturer or indirectly controlled by an agent of the manufacturer to be published records. Although the manufacturer may have a practice of granting access to product literature on a non-discriminatory basis, the manufacturer is in the sole position of being able to revise such literature without review. Although access to academic sources is similarly controlled, in general, publishers grant access to academic sources on a non-discriminatory basis, and academic sources are peer-reviewed. The author considers the scrutiny of peer review to be essential to the reliability of academic sources as published records. The lack of equivalent independent peer review of manufacturer product literature is a significant deficiency.

Where the author was unable to present adequate objective evidence, anecdotal evidence is presented, and is so noted.

In addition, from detailed review of technical guidance published by DARPA, technical proposals published by teams participating in the 2004 and 2005 GCE, and final published results, it is clear that published records are self-contradictory, provide incomplete or incorrect technical information, and do not provide enough information to answer key questions concerning team strategies during the 2004 and 2005 GCE, which would allow the author to independently assess the success of the DARPA Grand Challenge in one of its principal goals ([3], p. 2):

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

As a result, the decision was made early to reconcile published records with other published records where possible.

Since the conclusion of the 2007 Grand Challenge, the author has become aware of two additional sources of published records: a "privately compiled" collection of public domain files and documents ([70]) and a book about the Grand Challenge ([71]).

The publisher alternately stated the author of the collection ([70]) was the Department of Defense and: "Our news and educational discs are privately compiled collections of official public domain U.S. government files and documents - they are not produced by the federal government." ([72]). The author concluded review of the collection, as a "privately compiled" collection of public domain files and documents, would not result in improvement in quality over the existing published record. As a result, the author did not review the collection.

Review of the table of contents for the book ([71]) hosted by an Internet retailer ([72]) indicates the articles published by the Journal of Field Robotics constitute the majority of source material. The author concluded review of the book would not result in improvement in quality over the existing published record. As a result, the author did not review the book.

The 2004 and 2005 GCE were highly publicized, and received a great deal of attention from the public. DARPA stated: "There was significant publicity as a result of the event, which increased the public's awareness about the DoD desire to develop autonomous ground vehicles." ([3], p. 9). DARPA continued with a detailed description of media coverage of the 2004 GCE.

The author was ultimately unable to determine whether the DARPA Grand Challenge was an engineering challenge or an exercise in public relations, and believes the evidence supports a conclusion that DARPA was unable to adequately determine what problem Grand Challenge participants were being asked to solve because the difference between the stated goal of the Grand Challenge and actual goal of the Grand Challenge resulted in proposed solutions which did not result in significant progress toward the actual goal of the Grand Challenge. Offered solutions were too expensive, and improvement in challenge vehicle average speed was more a result of improvements in processing speed due to Moore's Law than any other factor.

As a result of the emphasis on public relations, DARPA made several unfortunate decisions concerning team participation. As a result of the enormity of the problem domain, teams did not have enough time to fully document their efforts, or complete all planned work or testing. Consequently, the overall quality of published records is low.

In addition, the precise definition of the Grand Challenge as a system integration exercise which required some expertise in the area of artificial intelligence applied to autonomous ground vehicle navigation was concealed by the format of the Grand Challenge as a race. Yet the results of the 2004 and 2005 GCE confirm this conclusion. The teams with the most experience in the problem domain were more successful, not because they were better able to code an artificial intelligence, but because they more quickly realized the limits of their sensors and computing equipment, and were able to optimize their solution to make full use of limited sensor technology.

In addition, if an unstated goal of DARPA was to “seed” industry with graduates

with experience in autonomous vehicle development, it was a failure. The Grand Challenge was not designed to reward or even emphasize the most important skill: competent system integration at a reasonable procurement cost.

Team 2005-12, for example, successfully completed[19] the major portion of the 2005 GCE course several weeks following the 2005 GCE, after having corrected the programming error responsible for failure to complete the course during the 2005 GCE. Team 2005-12 provided the following account ([74]):

> 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. [The challenge vehicle] 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"...
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> 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 [*sic*] 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 [the challenge vehicle'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, [the challenge vehicle] 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, [the challenge vehicle] 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, [the challenge vehicle] autonomously traversed the course. No changes, corrections or alterations were made to any of [the challenge vehicle's] autonomous systems. It can be argued that [the challenge vehicle] autonomously traversed an even more challenging course than that of the 2005 Grand Challenge. Except for the two lakes and the two “bulldozed” areas, [the challenge vehicle] was autonomous, including places where the road was significantly rougher than what

existed in early October.

This accomplishment is significant because Team 2005-12 is the only team known to have completed the 2005 GCE course, as described above, using only a STEREO sensor: one Point Grey Bumblebee stereo camera pair. No other environment sensors were in use by Team 2005-12. As a result, the author considers Team 2005-12 to be the most successful potentially-disruptive team to have participated in the 2005 GCE.

The most successful team overall, Team 2005-06, was not declared the winner of the 2005 GCE. This was because the fundamental problem of the Grand Challenge favored teams with significant experience and sponsorship. The utility of technical solutions proposed by other successful teams is suspect. It is unreasonable to expect the DOD to pay for a sensor package which exceeds a significant portion of the cost of the vehicle on which it installed. DARPA did not establish a relative weighting scheme which would allow challenge vehicle performance to be directly compared, and the published record is utterly inadequate to the task.

The use of simulation, including the development and application of standard reference terrain and standard problems, would provide a framework for evaluating the application of artificial intelligence to autonomous ground vehicle navigation free of the distraction of system integration problems which plagued teams participating in both the 2004 and 2005 GCE. As a result, the emphasis on artificial intelligence would be restored.

Teams participating in the Grand Challenge should first have been required to

implement a challenge vehicle in simulation. This would minimize real cost to the teams. In addition, some team programming hours would have been focused on improvements to the simulation environment.

The development and testing of a challenge vehicle should have been an iterative process, first of "tuning" the simulation environment to accurately model real world interaction, then increasing the difficulty and duration of field testing of team challenge vehicles via a series of challenges, moving from concept to an actual prototype and culminating in a 2004 or 2005 GCE-like event. This would have resulted in the development of a simulation environment which would have made it possible to fully separate the development of artificial intelligence applied to autonomous ground vehicle navigation from the system integration portion of the Grand Challenge, allowing continued participation by teams lacking the resources of some teams participating in the 2004 or 2005 GCE.

DARPA's selection of teams to continue to field testing should have been made on the basis of the performance of team implementation of a challenge vehicle controlling intelligence in simulation when compared to the real world. Field testing should have been accompanied by a requirement that teams participating in the Grand Challenge deliver periodic updates documenting the results of test and evaluation, culminating in an event similar to the 2004 or 2005 GCE.

In addition, teams participating in the Grand Challenge should have been provided a budget, required to follow basic accounting rules, and accounted for their expenses via the published record. This would have helped "level the playing field" by

mitigating the advantage of teams with significant sponsorship.