CHAPTER XIV. SYSTEM INTEGRATION WAS THE FUNDAMENTAL PROBLEM OF THE GRAND CHALLENGE

Throughout this chapter, system integration is described as "the fundamental problem of the Grand Challenge" or "the fundamental problem"[27].

The most conclusive evidence that the fundamental problem of the Grand Challenge was not software engineering or artificial intelligence but system integration, is *failure analysis*. See Chapter XIII. However, there were a number of other strategies common to the teams which support a conclusion that system integration was the fundamental problem of the Grand Challenge:

XIV.A. Identify the fundamental problem of the Grand Challenge

DARPA established the Grand Challenge to "promote innovative technical approaches that will enable the autonomous operation of unmanned ground combat vehicles". See Chapter I. However, DARPA did not award prize money on the basis of innovation in the field of autonomous ground vehicle technologies. DARPA awarded prize money to the first team to complete the 2005 GCE course. As a result, the actual goal of the Grand Challenge was concealed by the format of the Grand Challenge as a race.

The author considers the difference between the problem statement reported by DARPA and the fundamental problem of the Grand Challenge to be a contributing factor to the failure of some teams to accurately identify the problem and to solve what was essentially a "wrong problem", for example, the pre-mapping performed by Teams 2005-13 and 2005-14:

In a discussion of lessons learned from the Grand Challenge, Teams 2005-13 and 2005-14 stated: "Know the problem. Much of the technical approach described in this paper was excessive given the final form of the Grand Challenge. The groomed roads and carefully detailed route provided by the organizers greatly reduced two of the competitive advantages namely the H1 & HMMWV chassis and the preplanning system applied by the team. Furthermore, the team put an excess of wear-and-tear on the vehicles during testing operating on more rugged terrain than that encountered during the challenge. Had the final race conditions been known ahead of time, it would have been possible to shed a significant amount of technical complexity." ([24], p. 505).

The author considers solving a wrong problem diverted team resources which may have been used to more effectively solve the fundamental problem, or introduced unnecessary complexity by making the fundamental problem more difficult to solve.

Wrong problems variously solved by teams participating in the 2004 QID or GCE or 2005 GCE included:

XIV.A.1. Purpose-built vehicles

XIV.A.1.a. 2004

Six teams which participated in the 2004 QID selected purpose-built vehicles as challenge vehicle platform: Teams 2004-01, 2004-05, 2004-11, 2004-12, 2004-19, and 2004-24. See Table XIV. Five of the six teams did not complete the QID and were not selected to participate in the 2004 GCE: Teams 2004-01, 2004-05, 2004-11, 2004-12, and 2004-19. Team 2004-24 was selected to participate in the 2004 GCE, but withdrew prior to start ([30] and [3], p. 9).

XIV.A.1.b. 2005

Two teams which participated in the 2005 GCE selected purpose-built vehicles as challenge vehicle platform: Teams 2005-02 and 2005-20. See Table XIV. Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. Team 2005-02 completed 13.6 miles of the 2005 GCE course, less than the average.

Team 2005-20 completed 81.2 miles of the 2005 GCE course, the only team in either the 2004 or 2005 GCE to select a purpose-built vehicle as challenge vehicle platform and complete more than the average number of miles completed in either event.

Team 2005-20 stated: "[Team 2005-20] is a volunteer group of highly qualified ... engineers that specialize in the development of innovative technologies." Team 2005-20 reported the team was sponsored by a corporation "...which provides engineering, science and advanced technology solutions for the defense, security, transportation, environment, aerospace, and intelligent automation industries." ([56], p. 2).

In addition, Team 2005-20 stated: "The main goal of selecting a vehicle was to choose a vehicle that could handle the rough desert terrain with good handling characteristics, and acceptable acceleration performance while supplying a stable platform for the obstacle detection sensor array. This approach eliminates the need for complex gimbals and/or shock suppression suspensions for the sensor array. The major disadvantage of this approach is that the sensors look in a fixed direction requiring multiple sensors to cover the same zone that a single sensor could handle if it was gimbaled and pointed at the appropriate heading. The team researched several commercial trucks, military vehicles, and desert race vehicles before deciding on a custom-made chassis meeting all of our derived requirements." ([56], p. 3) and "The time spent in chassis specification and selection has paid off in safe reliable operation of [the challenge vehicle] on a variety of surfaces and at speeds and turning radiuses not achievable by either our previous Grand Challenge vehicle..., or by conventional SUV or pickup trucks." ([56], p. 15). The author concluded team experience and corporate sponsorship contributed to Team 2005-20's completion of 81.2 miles of the 2005 GCE course using a purpose-built vehicle as challenge vehicle platform.

However, Team 2005-20 also stated: “A concerted effort was put into the selection of the suspension components and tires to minimize unsprung weight and therefore minimize chassis motion during tire impact. The suspension links are lightweight and the wheel and tire combinations are the largest and lightest available on the market today.” and “Runflat or foam filled technologies were rejected owing to the additional unsprung weight of 60-100 lbs per tire.” ([56], pp. 3 - 4). Ironically, Team 2005-20's selection of lightweight components may have been the cause of the problem which prevented the team from completing the 2005 GCE. Team 2005-20 failed to complete the 2005 GCE due to a tire blowout, after the team challenge vehicle “started to exhibit some unusual behaviors” ([244]), possibly after leaving the course due to a bent frame.

XIV.A.1.c. Conclusions

Overall, the author concluded design and construction of a purpose-built vehicle represented a major development effort which diverted resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

The author considers the decrease in the number of purpose-built vehicles selected as challenge vehicle platform by teams which participated in the Grand Challenge from the 2004 QID to the 2004 GCE supports this conclusion. In addition, several teams explained the rationale behind their decision to select a commercially-available SUV or truck as challenge vehicle platform was influenced by similar concerns. For example:

- Team 2005-05

Team 2005-05 stated: “Reviewing the outcome of the 2004 Grand Challenge, we believe that generally speaking … vehicles based on commercial platforms did better than entirely custom-made vehicles. We felt this vindicated our choice of platform.” ([34], p. 2).

- Team 2005-09

Team 2005-09 stated: “The decision was made early to purchase a commercial vehicle rather than develop a custom platform. This has allowed the focus to be on issues more relevant to potential [Team 2005-09] sponsors including vehicle control, localization, navigation, and sensing/responding to the environment.” ([175], p. 2).

- Team 2005-10

Team 2005-10 stated: “The rational [*sic*] for this choice was that we didn’t want to spend time designing and building a vehicle. We wanted to spend time on the sensory and navigation systems, so we bought a commercial vehicle that was as close as possible to what was needed and modified it in the ways described above.” ([176], p. 2).

XIV.A.2. Proprietary sensors

Several teams which participated in the 2004 QID or GCE or 2005 GCE reported proprietary sensors were in use by the team. For example:

- Team 2004-04

Team 2004-04 stated: “One sensor is mounted on a rotating mechanism that enables it to scan multiple lines to produce a 3 dimensional data representation of the terrain.” ([44], pp. 8 - 9). Team 2004-04 participated in the 2005 GCE as Team 2005-02. Team 2005-02 also proposed using one rotating LIDAR sensor, however no rotating LIDAR sensor was in use by Team 2005-02 during the 2005 GCE. See below.

Both Teams 2004-04 and 2005-02 reported one rotating LIDAR sensor was in use via team technical proposals, and the rotating LIDAR sensor therefore represented a continuous development effort on the part of the team over a period of several years. The author concluded the Team 2004-04 rotating LIDAR sensor did not represent a major development effort on the part of the team, but diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

- Team 2004-06

Team 2004-06 developed a proprietary stereo camera pair for use during the 2004 GCE as the only obstacle and path detection sensor. See Table XXV. Team 2004-06 stated: “The vision system represents the major effort of the project.” ([114], p. 2).

In response to 2004 SQ 2.a and 2.b (see Table XXII), Team 2004-06 stated: “The vision system is functional and road testing will begin once the new sensors are operational.” and “Extensive tests are planned.” ([114], p. 3). The Team 2004-06 technical proposal ([114]) was dated February 20, 2004, approximately three weeks prior to the 2004 QID and GCE.

The author concluded the Team 2004-06 proprietary stereo camera pair represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Team 2004-06 participated in the 2005 GCE as Team 2005-03. Team 2005-03 developed a proprietary LIDAR sensor for use during the 2005 GCE. See below.

- Team 2004-22

Team 2004-22 developed a proprietary video system for use during the 2004 GCE as the only obstacle and path detection sensor. See Table XXV. Team 2004-22 reported very little additional identifying information for the components comprising their proprietary solution, and no additional identifying information for the cameras in use by the team. See paragraph V.C.22.c. Team 2004-22 twice referred to a “proprietary annex” which concealed technical detail. See paragraph V.E.2.f.

Despite a lack of sufficient technical detail, based on the capabilities reported by the team the author concluded the Team 2004-22 Video System represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the problem of system integration presented by the Grand Challenge.

- Team 2005-02

Team 2005-02 stated: “Also mounted on the sensor cage are two SICK ladars: one rotating ladar for 3D obstacle detection, the other fixed to scan the ground ahead of the vehicle for terrain slope estimation, tuned for negative obstacle detection.” ([167], p. 8). Team 2005-02 later stated: “Also mounted on the sensor cage are two SICK LADARs that scan the ground ahead of the vehicle for terrain slope estimation; one tuned for negative obstacle detection and the other for smooth terrain detection. Also, an additional SICK LADAR aimed parallel to the ground plane is mounted on the front of the vehicle at bumper level for planar obstacle detection.” ([50], p. 604).

Team 2005-02 did not report a rotating LIDAR sensor was in use by the team during the 2005 GCE via the Journal of Field Robotics. The author concluded a rotating LIDAR sensor was not in use by Team 2005-02.

However, both Teams 2004-04 and 2005-02 reported one rotating LIDAR sensor was in use via team technical proposals, and the rotating LIDAR sensor therefore represented a continuous development effort on the part of the team over a period of several years. The author concluded the Team 2005-02 rotating LIDAR sensor did not represent a major development effort on the part of the team, but diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. See paragraph VI.D. Team 2005-02 completed 13.6 miles of the 2005 GCE course, less than the average.

- Team 2005-03

Team 2005-03 developed a proprietary LIDAR sensor for use during the 2005 GCE as the only obstacle and path detection sensor. See Table XXVII. Team 2005-03 stated: “[Team 2005-03] designed and built all components in use for its DGC entry from the ground up dedicated for this purpose.” ([33], p. 6).

The author concluded the Team 2005-03 proprietary LIDAR sensor represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. See paragraph VI.D. Team 2005-03 completed 26.2 miles of the 2005 GCE course, less than the average.

Team 2005-03 was the only team which participated in both the 2004 and 2005 GCE to develop a different proprietary sensor as the only obstacle and path detection sensor in use by the team for each event.

- Team 2005-04

Team 2005-04 developed a proprietary RADAR sensor for use during the 2005 GCE. See Table XXVII. Team 2005-04 stated: "The second radar has a slewing dish antenna and is an in-house development." ([169], p. 8). The author concluded the Team 2005-04 proprietary RADAR sensor did not represent a major development effort on the part of the team, but diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. See paragraph VI.D. Team 2005-04 completed 29.0 miles of the 2005 GCE course, less than the average.

XIV.A.3. Navigation sensor integration

The author reviewed the published record to determine whether a Kalman filter or other sensor fusion strategy was in use by the teams, and whether teams implemented their own Kalman filter or other sensor fusion strategy, or it was a feature of a COTS component in use by the team. See Chapter VII.

The author concluded teams which independently implemented an other sensor fusion strategy diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge to attempt to solve a problem that had been solved by providers of COTS components at the time of the 2004 and 2005 GCE, not a problem of artificial intelligence, and were, in effect, solving a wrong problem. See paragraph VII.D.

XIV.A.4. Pre-mapping

Several teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team, including Team 2004-10, which completed 7.4 miles of the 2004 GCE course, the greatest number of miles completed by any team. Based on the strength of Team 2004-10's performance during the 2004 GCE, the author reviewed the published record to determine whether pre-mapping provided a competitive advantage to teams which participated in the 2004 QID or GCE or 2005 GCE and which reported pre-mapping was in use. See Chapter XI.

The author concluded it was possible to successfully complete the 2005 GCE without the use of pre-mapping, and that pre-mapping was not a key factor. However, the author concluded pre-mapping may address certain vulnerabilities reported by teams participating in the 2004 QID or GCE or 2005 GCE: terrain features indicative of the presence of water and significant changes in elevation. In addition, the author concluded the use of external map data during the 2004 GCE may have required teams to implement overly-complex solutions to the problem of autonomous navigation, and may, in fact, have been a wrong problem solved by some teams which diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge. See paragraph XI.D.

XIV.A.5. Team 2004-03 self-stabilizing motorcycle

Team 2004-03 selected a motorcycle as challenge vehicle platform. See Table XIV. In response to 2004 SQ 2.a (see Table XXII), Team 2004-03 described test and evaluation performed to date to develop a self-stabilizing motorcycle ([92], pp. 6 - 7). Although Team 2004-03 has headings for other tests including "DGPS correction", "GPS waypoint navigation", and "RDDF processing", Team 2004-03 did not report any previous or planned tests in these areas as of the March 1, 2004 revision of their technical proposal, approximately one week prior to the first day of the 2004 QID on March 8, 2004.

The author concluded the self-stabilizing motorcycle described by Team 2004-03 represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

XIV.A.6. Team 2004-21 programming language, compact "standard and solar charging system", and "hybrid navigational system"

Team 2004-21 stated ([155], p. 4, *emphasis in original*):

> The microcontrollers will be programmed in their native Forth language and the Pentium class machine(s) will be programmed in "**Hoopla**", a custom programming language with many features not found in other languages...
>
> (**Hoopla** – Hierarchical **O**bject **O**riented **P**rogramming **La**nguage.)
>
> Hoopla is a set of application-specific words (using **Forth** as a base language) that define an environment

> that can quickly react to interrupting conditions with predefined decision tables controlling how the vehicle should react to the interrupting conditions. Hoopla basically turns every sensory condition into an action similar to the way in which biological nervous systems react to stimulus such as a pin-prick or a bruising. Combining what might be called the **"Best of AI"**, Hoopla is best described as (1) a set of sensory objects that combine (2) an Artificial Neural Network with (3) predefined methods that take the form of (4) a decision tree/expert system.

An Internet search using the key words "HOOPLA" or "Hierarchical Object Oriented Programming Language" as the search string revealed several programming languages named "Hoopla" exist, including some with sound-alike names such as "HOPL" or "HOOPLE" and a periodical about object-oriented programming languages named HOOPLA ("Hooray for Object Oriented *Programming Languages*!"). Some of these references pre-date the 2004 GCE by several years, while others are more recent developments. However, none of the programming languages named "Hoopla" conform to the Team 2004-21 description of Hoopla, above.

In addition to the Team 2004-21 programming language, Team 2004-21 also stated: "Extra power will be provided by standard and solar charging system. Our design is more compact and more efficient than anything ever used before. This too is new technology." ([155], p. 3) and "We will be using terrain following technology, this is a hybrid navigational system unlike anything used before, a composite of many systems working together." ([155], p. 6).

The author concluded Hoopla, as described by Team 2004-21, the compact "standard and solar charging system", and the "hybrid navigational system" represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

XIV.B. Reduce complexity

XIV.B.1. Reduce the number of components

XIV.B.1.a. Eliminate unnecessary state sensors

Via 2004 SQ 1.f.1 and 1.f.2 (see Table XXII), DARPA requested teams report: "What sensors does the challenge vehicle use for sensing vehicle state?" and "How does the vehicle monitor performance and use such data to inform decision making?" The author completed a comprehensive review of technical proposals submitted by teams participating in the 2004 QID or GCE to determine if team technical proposals reported sufficient technical detail to identify the quantity, manufacturer, and model number for state sensors in use by the teams.

Via 2005 SQ 2.3.3 (see Table XXIII), DARPA requested teams report: “Describe the internal sensing system and architecture used to sense the vehicle state.” The author did not complete a comprehensive review of 2005 NQE and GCE technical proposals. The author did not attempt to determine if 2005 technical proposals reported enough information to determine the quantity, manufacturer, and model number for state sensors in use by the teams. See paragraph V.B.2.

The author asserts these questions predisposed some teams to implement unnecessary state sensors. For example:

XIV.B.1.a.i. Fuel level monitoring sensors

XIV.B.1.a.i.a. 2004

Three of 25 teams participating in the 2004 QID or GCE reported fuel level monitoring sensors were in use by the team: Teams 2004-01, 2004-08, and 2004-21. No 2004 challenge vehicle had a maximum range of less than the reported 142-mile course length (see Table LXX).

However, DARPA revised the proposed 2004 GCE course length continuously in the months prior to the date team technical proposals were required to be submitted to DARPA. Teams were required to implement a challenge vehicle which could traverse a course of these lengths and describe their implementation via their technical proposals. DARPA stated the proposed 2004 GCE course length would be 300 miles on February 22, 2003, “approximately 250 miles” on June 18, 2003, and “approximately 210 miles” on November 26, 2003. See Appendix C.

Team technical proposals were required to be submitted to DARPA by October 14, 2003, approximately two and one-half months before DARPA published revision “5 January 2004” of the 2004 GCE rules which eliminated the “Checkpoint Area” the author determined was located near the midway point of the proposed 2004 GCE course and after DARPA stated the proposed 2004 GCE course length would be 250 miles.

As a result, the author selected proposed 2004 GCE course length of 250 miles as representative of the expected course length prior to January 5, 2004, and on the date by which teams participating in the 2004 GCE were required to submit a complete technical description of their challenge vehicles to DARPA, including reported range.

Three teams reported a range of less than a proposed 2004 GCE course length of 250 miles: Teams 2004-03, 2004-10, and 2004-16. See Table LXX.

Neither Team 2004-03, 2004-10, nor 2004-16 reported fuel level monitoring sensors were in use by the team, and all thee teams were selected to participate in the

2004 GCE. Team 2004-10 completed 7.4 miles of the 2004 GCE course, the best performance by any team. As a result, the author concluded fuel level monitoring sensors were unnecessary. This does not explain why Teams 2004-03, 2004-10, and 2004-16 did not implement a challenge vehicle capable of traversing a course length of 250 miles. The author proposes a discussion between DARPA, several of the teams with prior experience, and others resulted in the reduction in proposed course length to a length which could be completed within the reported ranges of all challenge vehicles, and that this discussion was the basis for the eventual reduction of the proposed 2004 GCE course length from 250 miles to less than 150 miles.

In contrast, none of the three teams which reported fuel level monitoring sensors were in use by the team performed well in the 2004 QID or were selected to participate in the 2004 GCE:

- Team 2004-01

Team 2004-01 passed on their turn on the first day of the 2004 QID, and terminated within the starting chute area on the last day of the 2004 QID. Team 2004-01 was not selected to participate in the 2004 GCE. See paragraph V.C.1.

- Team 2004-08

Team 2004-08 did not participate in the 2004 QID or GCE due to “lack of funding”. See paragraph V.C.8.

- Team 2004-21

Team 2004-21 passed on their turn on the first day of the 2004 QID, terminated their attempt on the third day of the 2004 QID, and officially withdrew on the last day of the 2004 QID. Team 2004-21 was not selected to participate in the 2004 GCE. See paragraph V.C.21.

XIV.B.1.a.i.b. 2005

No team which participated in the 2005 GCE reported fuel level monitoring sensors were in use by the team. DARPA did not revise the proposed course length of 175 miles after the 2005 GCE rules were published on October 8, 2004. See Appendix C.

However, no team which participated in the 2004 GCE reported a challenge vehicle range of less than 175 miles. See Table LXX. 175 miles was less than the minimum range reported by Team 2004-10 of approximately 186.5 miles. Team 2004-10 participated in the 2005 GCE as Team 2005-13. The author proposes this may explain why the 2005 GCE rules established a proposed 2005 GCE course length of “no longer than 175 miles” ([2], p. 4), after DARPA decreased the proposed 2004 GCE course length from 300 miles to “approximately 250 miles” and then “approximately 210 miles”[28].

XIV.B.1.a.ii. Temperature monitoring sensors

XIV.B.1.a.ii.a. 2004

Nine of 25 teams participating in the 2004 QID or GCE reported temperature monitoring sensors were in use by the team: Teams 2004-01 (“water temperature”), 2004-05 (“cooling water temperature”), 2004-15 (“air conditioning information”), 2004-18 (“temperature sensors to monitor engine and other critical components”), 2004-20 (“temperature”), 2004-21 (“temperature”), 2004-22 (“temperature sensors” for “engine, oil, and outside temperatures”), 2004-24 (“water temperature” for the Challenge vehicle's generators), and 2004-25 (“temperature inside all electronic enclosures”). In addition, Team 2004-17 reported OEM OBD-II sensors were in use by the team to monitor “engine temperature”. See Table XXIV. With the exception of Teams 2004-15, 2004-24, and 2004-25 the teams reported temperature sensors were in use to monitor the state of the challenge vehicle's engine.

Six of the nine teams which reported temperature monitoring sensors were in use by the team were not selected to participate in the 2004 GCE: Teams 2004-01, 2004-05, 2004-15, 2004-20, 2004-21, and 2004-22. See paragraphs V.C.1., V.C.5., V.C.15., V.C.20., V.C.21., and V.C.22.

Three of the nine teams which reported temperature monitoring sensors were in use by the team were selected to participate in the 2004 GCE: Teams 2004-18, 2004-24, and 2004-25. Team 2004-24 withdrew prior to start, Team 2004-25 completed zero miles of the 2004 GCE course, and Team 2004-18 completed 0.20 miles of the 2004 GCE course ([30] and [3], p. 8). Team 2004-18 was the only team which participated in the 2004 GCE and reported temperature monitoring sensors were in use by the team to have completed more than zero miles of the 2004 GCE course.

XIV.B.1.a.ii.b. 2005

Six teams which participated in the 2005 GCE reported temperature monitoring sensors were in use by the team, two pairs of which were co-participants:

- Team 2005-08

Team 2005-08 reported a “Temperature Monitor” via Figure 2 (“Hardware Configuration”) of the team technical proposal ([173], p. 7). Team 2005-08 stated: “The computing hardware is located in a common environmental enclosure in the bed of the F250.” and “The environmental enclosure is cooled using a stock Ford Excursion auxiliary air conditioning unit mounted in the truck bed.” ([173], p. 5). Team 2005-08 did not participate in the 2004 QID or GCE, and completed 14.0 miles of the 2005 GCE course.

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “[The challenge vehicle's] state sensing monitors and measures equipment temperature, actuator position, velocity and acceleration. State is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), thermocouples, current and voltage sensors.” ([11], p. 10 and [12], p. 10). Team 2005-13 participated in the 2004 QID and GCE as Team 2004-10. Teams 2005-13 and 2005-14 successfully completed the 2005 GCE course. However, Teams 2005-13 and 2005-14 had prior experience and extensive corporate and academic sponsorship.

- Team 2005-19

Team 2005-19 stated: “The [challenge vehicle controlling intelligence] also monitors vehicle health, and has the capability of adjusting vehicle behavior based on engine and generator temperatures, as well as several other vehicle health metrics.” ([55], p. 13). Team 2005-19 did not participate in the 2004 QID or GCE, and completed 8.9 miles of the 2005 GCE course.

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: “[The challenge vehicle] uses an on-board accelerometer array with [a] temperature sensor located in the electronics enclosure to measure the conditions to which the vehicle electronics are subject. Battery voltage is also logged on the vehicle’s power system... This information does not affect the vehicle’s navigation behavior.” ([58], p. 7 and [164], p. 9). Team 2005-22 participated in the 2004 QID and GCE as Team 2004-25. Teams 2005-22 and 2005-23 completed 43.5 and 39.4 miles of the 2004 GCE course, respectively.

XIV.B.1.a.iii. Results

- 2004

The author is not confident sufficient technical detail was reported by DARPA to determine the cause of failures encountered by teams participating in the 2004 QID or GCE. For example, DARPA reported the Team 2004-17 challenge vehicle “...veered off course, went through a fence, tried to come back on the road, but could not get through the fence again.” and the Team 2004-18 challenge vehicle “...began smoothly, but at mile 0.2, when making its first 90-degree turn, the vehicle flipped.” ([3], p. 8).

Neither of these problems is directly attributable to implementation of fuel level or temperature monitoring sensors, or any other state sensors, and the author considers it unlikely that implementation of unnecessary state sensors was a direct cause of failure to complete the 2004 QID or GCE. The author asserts the complexity observed in some team technical proposals is an indicator of another problem: lack of experience.

Teams 2004-01, 2004-04, 2004-05, 2004-10, 2004-15, 2004-18, 2004-20, and 2004-24 reported large numbers of state sensors (five or more) were in use by the team: engine RPM, "intake manifold pressure", fuel level, various temperature, transmission position, throttle position, steering angle, various suspension, "low oil pressure", driveshaft RPM, various voltage, various current, or otherwise unspecified sensors were in use by the teams.

Four of eight teams which reported large numbers of state sensors were in use by the team participated in the 2004 QID but were not selected to participate in the 2004 GCE: Teams 2004-01 (nine sensors), 2004-05 (nine sensors), 2004-15 (eight sensors), and 2004-20 (five sensors). None of these teams reported prior experience. Teams 2004-01, 2004-05, and 2004-15 reported only limited corporate or academic sponsorship. Team 2004-20 reported moderate corporate sponsorship.

Four of eight teams which reported large numbers of state sensors were in use by the team participated in the 2004 QID and were selected to participate in the 2004 GCE: Teams 2004-04 (five sensors), 2004-10 (five sensors), 2004-18 (five sensors), and 2004-24 (eight sensors). Team 2004-04 reported prior experience, moderate corporate sponsorship, and extensive academic sponsorship, and completed 0.45 miles of the 2004 GCE course. Team 2004-10 reported prior experience and extensive corporate and academic sponsorship and completed 7.4 miles of the 2004 GCE course. Team 2004-18 reported no prior experience and moderate corporate sponsorship and completed 0.2 miles of the 2004 GCE course. Team 2004-24 reported no prior experience and no sponsorship and withdrew prior to start.

- 2005

Based on the failure analysis performed by the author (see Chapter XIII.), there is no evidence fuel level monitoring sensors, temperature monitoring sensors, or any other state sensors directly contributed to the failure of any team which participated in the 2005 GCE to complete the course. There is no evidence the implementation of these sensors contributed to the success of any team which participated in the 2005 GCE.

XIV.B.1.a.iv. Conclusions

The decision to implement unnecessary state sensors reported by some teams prior to the 2004 QID or GCE or 2005 GCE contributed to poor performance by increasing the complexity of the challenge vehicle, requiring teams to divert resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

In addition, the author concluded the effect of experience may have allowed teams with prior experience in the field of autonomous vehicle development (e.g., 2004-04, 2004-10, 2005-02, 2005-13, and 2005-14) or prior experience in the 2004 GCE (e.g., Teams 2005-22 and 2005-23) to have implemented these sensors, supporting a conclusion that the lack of experience was a significant barrier to entry. See paragraph X.D.1.

In the extreme cases of teams which reported eight or more state sensors were in use by the team, the published record confirms lack of experience or limited sponsorship prevented teams which were otherwise considered competitive by DARPA from participating in either the 2004 or 2005 GCE, demonstrating that, for some teams, lack of experience or limited sponsorship was an insurmountable obstacle:

- Team 2004-01

Team 2004-01 reported what information the unknown state sensors (see Table XXIV) in use by the team provided, but the team did not report how the team intended to combine state sensor output to produce useful information for the challenge vehicle controlling intelligence.

Team 2004-01 stated: "We realize there is probably so much we don't know so we try to keep everything as brutally simple as possible. We are trying to avoid dependence on overly sophisticated systems which may be more prone to failure and less able to adapt to an unexpected set of conditions." ([81]).

Team 2004-01 passed on their turn on the first day of the 2004 QID, and terminated within the starting chute area on the last day of the 2004 QID. Team 2004-01 was not selected to participate in the 2004 GCE. See paragraph V.C.1. DARPA stated only that Team 2004-01 "terminated within the starting chute area" ([79]). However, in private communication with the author the Team 2004-01 team leader attributed the cause of the problem to an unknown system integration failure caused by "severe lack of time" ([239]).

Team 2004-01 was selected as a semifinalist to participate in the 2005 NQE, but did not complete the 2005 NQE and was not selected to participate in the 2005 GCE ([242]).

- Team 2004-05

2004-05 reported what information the unknown state sensors (see Table XXIV) in use by the team provided, but the team did not report how the team intended to combine state sensor output to produce useful information for the challenge vehicle controlling intelligence.

The Team 2004-05 team website was no longer available. However, their "Team Information" on the Archived Grand Challenge 2005 website ([19]) stated, in part: "We are a group of volunteers that have 'day jobs' and know we can make a difference by being part of this history making event. Our numbers continue to grow as people learn of our goals. All are welcome regardless of the amount of time available to participate or specialty. It is exciting to be around so much energy and intellectual capital."

Team 2004-05 was delayed awaiting parts for the challenge vehicle until the third day of the 2004 QID, and officially withdrew on the last day of the 2004 QID. See paragraph V.C.5.

Team 2004-05 was selected as a semifinalist to participate in the 2005 NQE, but did not complete the 2005 NQE and was not selected to participate in the 2005 GCE ([242]).

- Team 2004-15

2004-15 reported what information the unknown state sensors (see Table XXIV) in use by the team provided, but the team did not report how the team intended to combine state sensor output to produce useful information for the challenge vehicle controlling intelligence.

Team 2004-15 stated: "Although the team has worked diligently and sacrificed much in our effort to have [the challenge vehicle] ready for the March Grand Challenge, it is not to be. We made great strides and were on the right track as evidenced by our inclusion in the first group invited to the QID. Unfortunately, we fell victim to everyone's problem of 'not enough time' and 'not enough money'." ([136]).

Although Team 2004-15 applied to participate in the 2005 GCE, the team was not selected as a semifinalist to participate in the 2005 NQE ([242]).

Overall, the author concluded the performance of teams which implemented unnecessary state sensors confirms the effects of experience and sponsorship, and asserts this effect was *lasting*. Teams which were unable to overcome lack of experience or limited sponsorship were not competitive with teams which had prior experience or significant corporate or academic sponsorship.

Teams with prior experience or extensive corporate or academic sponsorship were able to use their experience, in particular, and sponsorship as the equivalent of a "force multiplier". The advantage this gave these teams was so significant that the author questions whether it was appropriate for DARPA to allow most of the teams which participated in the 2004 or 2005 GCE to participate without first ensuring those teams were able to identify the fundamental problem and devote sufficient resources to the development of a challenge vehicle which would be competitive with those of teams with prior experience and significant sponsorship.

XIV.B.1.b. Leverage the capabilities of the challenge vehicle platform

XIV.B.1.b.i. Electrical power generation strategies

In general, team strategies to provide electrical power to the challenge vehicle's computing hardware and sensors fall into four categories: exclusive use of the challenge vehicle alternator, challenge vehicle alternator and batteries, exclusive use of an external generator, or external generator and batteries. The author performed a comprehensive review of team technical proposals to determine what strategy was in use by teams which participated in the 2004 or 2005 GCE. Teams which only participated in the 2004 QID were excluded from this review.

Some teams reported one or more alternators or one or more generators were in use by the team. The author did not distinguish between teams using one or more alternators or one or more generators, except to note that it increased redundancy. See paragraph XIV.C. In addition, teams alternately referred to the use of challenge vehicle batteries (i.e., for the challenge vehicle's starter motor) and batteries which were part of the power generation system. When evaluating the use of batteries, the author considered only additional batteries installed as part of the challenge vehicle's power system to be “batteries”, even if the team referred specifically to the use of challenge vehicle batteries to provide electrical power. In addition, several teams reported the use of an Uninterruptible Power Supply (UPS). For the purposes of this analysis, the author considers a UPS to be a battery.

Tabulated results are presented by Tables LXXI and LXXII. The results do not support a conclusion that any particular electrical power generation strategy was “best”. However, the published record supports conclusions that some strategies were more effective than others:

- There was a net migration from the use of generators to the use of challenge vehicle alternators to generate electrical power. Seven of 15 (47 percent) teams which participated in the 2004 GCE reported an alternator or alternator and batteries were in use by the team, compared to 12 of 21 (57 percent) teams which participated in the 2005 GCE.

- Five of ten (50 percent) teams which participated in the 2004 GCE and did not select a commercially-available ATV as challenge vehicle platform reported an alternator or alternator and batteries were in use by the team, compared to 11 of 17 (65 percent) of teams which participated in the 2005 GCE.

- The use of an external generator or external generator and batteries was a common strategy among teams which participated in the 2004 GCE regardless of challenge vehicle platform. Teams which reported an external generator or external generator and batteries were in use variously selected a commercially-available SUV, commercially-available truck, commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform.

- The use of an external generator or external generator and batteries was *not* a common strategy among teams which participated in the 2005 GCE. In general, teams which reported an external generator or external generator and batteries were in use selected a commercially-available ATV as challenge vehicle platform, with the exception of the following teams: Teams 2005-13, 2005-14, 2005-18, and 2005-19.

- No team which participated in the 2005 GCE and reported an external generator or external generator and batteries were in use and which selected a commercially-available ATV as challenge vehicle platform completed more than 48.3 miles of the 2005 GCE course, the average number of miles completed.

- The use of an external generator or external generator and batteries may have been a consequence of selection of a commercially-available ATV as challenge vehicle platform, but an alternate strategy was in use by Team 2005-11. Team 2005-11 stated: "...the OEM 12-volt generator is augmented with an additional 65 amp, 24 volt alternator and high capacity batteries." ([182], p. 5). Team 2005-11 had no prior experience and completed 7.2 miles of the 2005 GCE course.

- Teams 2005-13 and 2005-19 selected a military service vehicle as challenge vehicle platform. The use of an external generator or external generator and batteries may have been a consequence of selection of a military service vehicle as challenge vehicle platform[29]. Team 2005-13 had prior experience and successfully completed the 2005 GCE. Team 2005-19 had no prior experience and completed 8.9 miles of the 2005 GCE course.

- Seven teams completed more than 48.3 miles of the 2005 GCE course, the average number of miles completed: Teams 2005-01, 2005-06, 2005-13, 2005-14, 2005-16, 2005-20, and 2005-21. With the exception of Teams 2005-06, 2005-13, and 2005-14, an alternator or alternator and batteries were in use by all teams which completed more than the average number of miles of the 2005 GCE course.

- Team 2005-06 was the only team with no prior experience which successfully completed the 2005 GCE. The electrical power generation strategy in use by Team 2005-06 was unique. Team 2005-06 selected a 2005 Ford Escape Hybrid as challenge vehicle platform. See Table XVI.

  Team 2005-06 stated: "...the hybrid's electrical system, which is powered by a 330-volt battery, provides over 1300 watts of power to the equipment mounted in the vehicle. This alleviates [Team 2005-06] from having to use a generator to provide power for the computer equipment." ([172], p. 3); "Rather than use a generator, [Team 2005-06] chose to use the Escape Hybrid's integrated electrical system to provide 12 volts of power for all of its computer and navigation equipment. The Escape Hybrid provides 110 amps of power at 12 volts, which is more than adequate to power all of [Team 2005-06's] equipment." ([172], p. 5); and "The Grand Challenge could require a vehicle to be paused for extended periods of time. This could cause problems for many vehicles due to excess fuel consumption during the pause. Most vehicles will not want to shut down their navigation systems during a pause, so an extended pause could tax both their generator's fuel supply and the vehicle's own fuel supply. The Escape Hybrid will run off electrical power during pauses and will only start the gas engine when necessary to recharge the battery. This will help ensure that [Team 2005-06's] vehicle will not need to shut down any systems, yet still have the fuel necessary to finish the Grand Challenge." ([172], p. 3).

As a result, by careful selection of the platform for their challenge vehicle, Team 2005-06 was able to leverage the capabilities of the challenge vehicle platform to provide power for computing hardware and navigation sensors[30].

Overall, the author considers the results of the review support the following key factors:

- Identify the fundamental problem of the Grand Challenge. Selection of challenge vehicle platform may have unintended consequences.

- Leverage the capabilities of the challenge vehicle platform. Use the challenge vehicle alternator or alternator and batteries to provide electrical power to the challenge vehicle's computing hardware and sensors, if possible.

- Reduce complexity. Do not implement an electrical power generation strategy through exclusive use of an external generator or external generator and batteries, unless necessary.

In addition, the author considers the results of the review confirm the effects of experience and sponsorship.

XIV.B.1.b.ii. Computing hardware cooling strategies

Several teams reported the challenge vehicle air conditioning system or dedicated, air-conditioned enclosures were in use to cool computing hardware, or selected components able to withstand high temperatures. For example:

- Team 2004-09

Team 2004-09 stated: "Vehicle air conditioning will provide the required cooling to ensure that the ambient conditions of the processing equipment are within published tolerance." ([47], p. 3). Team 2004-09 selected a commercially-available SUV as challenge vehicle platform. See Table XV. As a result, Team 2004-09 was able to leverage the vehicle's air conditioning system. Team 2004-09 had no prior experience, moderate corporate sponsorship, and limited academic sponsorship. See Table LXVI. Team 2004-09 was selected to participate in the 2004 GCE, but completed zero miles of the 2004 GCE course.

- Team 2004-10

Team 2004-10 stated: "E-box cooling system was designed and implemented, based on analyzed and measured thermal characteristic data." ([77], p. 6). Team 2004-10 selected a military service vehicle as challenge vehicle platform. See Table XV. As a result, Team 2004-10 was not able to leverage the vehicle's air conditioning system. Team 2004-10 had prior experience and extensive corporate and academic sponsorship. See Table LXVI. Team 2004-10 completed 7.4 miles of the 2004 GCE course, the best performance by any team.

- Team 2004-25

Team 2004-25 reported "cooling fans" were in use by the team via Table 1 ("Estimated Peak Power Consumption") of the team technical proposal ([49], p. 4) and stated: "...we expect to monitor... the temperature inside all electronic enclosures." ([49], p. 11). Team 2004-25 selected a commercially-available ATV as challenge vehicle platform. See Table XV. As a result, Team 2004-25 was not able to leverage the vehicle's air conditioning system. Team 2004-25 had no prior experience and moderate corporate and academic sponsorship. See Table LXVI. Team 2004-25 was selected to participate in the 2004 GCE, but completed zero miles of the 2004 GCE course.

- Team 2005-06

Team 2005-06 stated: "In order to ensure that the best computing hardware was chosen, [Team 2005-06] investigated the leading computing hardware used by several different industries. The marine industry offered a ready made system that included protection from excessive shock, high temperatures, and other environmental issues. [The system]... hosts all of the main computing functions, such as sensor communication, vehicle controls, and artificial intelligence." ([172], p. 7).

Team 2005-06 later stated ([28], p. 512):

> After initial testing during a hot summer day, we noticed that the computing equipment was overheating and then malfunctioning due to the high temperatures in the cabin of the car. This revealed an issue between having proper fuel efficiency and having an acceptable cabin temperature. If the air conditioner

> was kept on its highest setting, the equipment did not overheat, but the resulting fuel economy was projected to be too low to finish the expected 175 mile race (projections were based on the fuel economy of the 2005 Ford Escape 4 cylinder model). This lowered fuel economy was due to the fact that if the air conditioning system on a Ford Escape Hybrid is set to its maximum setting, then the compressor must run constantly, which causes the gasoline engine to also run constantly. This defeats the whole fuel efficient design of the hybrid's engine as explained previously.
>
> As a result of this problem, we created a simple on/off mechanism for the air conditioning system that was suited to the cooling needs of the equipment rather than the passenger's comfort. The device consisted of a temperature sensor, a BASIC stamp, and a servomotor. We mounted the servo to the air conditioning system's control knob so that the servo could turn the air conditioner on and off. The BASIC stamp is a simple programmable microcontroller with eight bidirectional input and output lines and a limited amount of memory which can hold a small program. We programmed the BASIC stamp to monitor the temperature of the cabin near the equipment. If the temperature dropped below a certain threshold, the air conditioner was turned off. If the temperature rose above a certain temperature, the air conditioning system was turned to its maximum setting. This simple system solved our temperature problems while not adversely affecting our fuel efficiency, yet still only interfacing with the vehicle at its highest level.

As a result, Team 2005-06 selected components able to withstand high temperatures and was able to leverage the vehicle's air conditioning system. Team 2005-06 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-06 successfully completed the 2005 GCE.

- Team 2005-08

Team 2005-08 stated: "The computing hardware is located in a common environmental enclosure in the bed of the F250." and "The environmental enclosure is cooled using a stock Ford Excursion auxiliary air conditioning unit mounted in the truck bed." ([173], p. 5). Team 2005-08 selected a commercially-available truck as challenge vehicle platform. See Table XVI. Because Team 2005-08 located computing hardware in an “environmental enclosure” in the bed of the challenge vehicle, Team 2005-08 was not able to leverage the vehicle's air conditioning system. Team 2005-08 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-08 completed 14.0 miles of the 2005 GCE course.

- Team 2005-09

Team 2005-09 stated: “We desired a vehicle that would be street legal with sufficient off-road capabilities as well as a protected interior that would keep the components cooled and not exposed to the elements... The SportTrac ... has sufficiently cooled interior space for our computing equipment.” ([175], p. 2). Team 2005-09 selected a commercially-available SUV as challenge vehicle platform. See Table XVI. As a result, Team 2005-09 was able to leverage the vehicle's air conditioning system. Team 2005-09 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-09 completed 0.7 miles of the 2005 GCE course.

- Team 2005-10

Team 2005-10 stated: “Standard equipment includes... air conditioning... The rational [*sic*] for this choice was that we didn’t want to spend time designing and building a vehicle. We wanted to spend time on the sensory and navigation systems, so we bought a commercial vehicle that was as close as possible to what was needed and modified it in the ways described above.” ([176], p. 2). Team 2005-10 selected a commercially-available SUV as challenge vehicle platform. See Table XVI. As a result, Team 2005-10 was able to leverage the vehicle's air conditioning system. Team 2005-10 had no prior experience and limited corporate sponsorship. See Table LXVII. Team 2005-10 completed 23.0 miles of the 2005 GCE course.

- Team 2005-13

Team 2005-13 stated: “A custom aluminum body and a cooled, shock-isolated electronics bay replaced the crew compartment body panels, doors, seats and windshield.” ([11], p. 2). Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE. Team 2005-14 did not report the cooling solution in use by the team. Team 2005-13 selected a military service vehicle as challenge vehicle platform. See Table XVI. As a result, Team 2005-10 was not able to leverage the vehicle's air conditioning system. Team 2005-13 had prior experience and extensive corporate and academic sponsorship. See Table LXVII. Team 2005-13 successfully completed the 2005 GCE.

- Team 2005-15

Team 2005-15 stated: “We use two 750 MHz Pentium-4 embedded systems built as a PC104+ stack. These two computers do not require active cooling.” ([53], p. 6). Team 2005-15 selected a commercially-available ATV as challenge vehicle platform. See

Table XVI. As a result, Team 2005-15 was not able to leverage the vehicle's air conditioning system. Team 2005-15 had no prior experience and moderate corporate and academic sponsorship. See Table LXVII. Team 2005-15 completed 15.9 miles of the 2005 GCE course.

- Team 2005-16

Team 2005-16 stated: “The computing system is located in the vehicle’s trunk, as shown in Fig. 2. Special air ducts direct air flow from the vehicle’s AC system into the trunk for cooling.” ([195], p. 4). Team 2005-16 selected a commercially-available SUV as challenge vehicle platform. See Table XVI. As a result, Team 2005-16 was able to leverage the vehicle's air conditioning system. Team 2005-16 had prior experience and extensive corporate and academic sponsorship. See Table LXVII. Team 2005-16 successfully completed the 2005 GCE.

- Team 2005-20

Team 2005-20 stated: “This experience has led to redesign of some components of the vehicle, improved cooling for computers, and knowledge of critical spare parts to have on hand.” ([56], p. 14). Team 2005-20 selected a purpose-built vehicle as challenge vehicle platform. See Table XVI. As a result, Team 2005-20 was not able to leverage the vehicle's air conditioning system. Team 2005-20 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-20 completed 81.2 miles of the 2005 GCE course. Although Team 2005-20 did not describe the method by which computing hardware was cooled, the team described “improved cooling for computers” as a result of their test and evaluation program.

- Team 2005-21

Team 2005-21 stated: “...all the computers are housed in a closed container which is cooled with a closed-loop, filtered, air-conditioning system.” ([160], p. 3). Team 2005-21 selected a military service vehicle as challenge vehicle platform. See Table XVI. As a result, Team 2005-21 was not able to leverage the vehicle's air conditioning system. Team 2005-21 had prior experience and extensive corporate sponsorship. See Table LXVII. Team 2005-21 completed the 2005 GCE, but was not successful.

Overall, the author considers the cited examples support the following key factors:

- Identify the fundamental problem of the Grand Challenge. Select a challenge vehicle platform with capabilities that may be leveraged.

- Leverage the capabilities of the challenge vehicle platform. Use the challenge vehicle air conditioning system to cool computing hardware, if possible.

- Leverage existing COTS components. Use components which do not require the team to implement a cooling strategy, if necessary.

- Perform adequate test and evaluation. Adequate test and evaluation may identify weaknesses in team implementation of a cooling strategy.

In addition, the author considers the cited examples confirm the effects of experience and sponsorship.

XIV.B.1.b.iii. Suspension

Several teams reported the challenge vehicle suspension was in use to reduce the impact of off-road terrain on computing hardware and sensors[31], frequently in combination with an additional level of shock isolation. For example:

- Team 2005-06

Team 2005-06 stated: "...the Escape Hybrid is a very narrow four wheel drive vehicle with a very smooth suspension... The smooth suspension also ensures that the rough terrain will have less impact on the equipment mounted in the vehicle." ([172], p. 3).

- Team 2005-13

Team 2005-13 stated: "The chassis suspension utilizes custom coil-over struts with nitrogen reservoirs... [The challenge vehicle's] electronics enclosure is suspended with 12 shock isolators, each of which is a coil over strut shock absorber... These two levels of suspension serve (1) to protect [the challenge vehicle's] sensitive electronics and computing hardware and (2) to smooth sensor trajectories." ([11], pp. 2 - 3).

- Team 2005-14

Team 2005-14 stated: "The chassis suspension utilizes custom coil-over struts with nitrogen reservoirs and a central tire inflation system... [The challenge vehicle's] electronics enclosure sits on a semi-active modified Stewart Platform. Each shock isolator of the Stewart platform is a coil-over strut with a magnetorheological fluid damper... These two levels of suspension serve to protect [the challenge vehicle's] sensitive electronics and computing hardware." ([12], pp. 2 - 3).

- Team 2005-20

Team 2005-20 stated: “The main goal of selecting a vehicle was to choose a vehicle that could handle the rough desert terrain... while supplying a stable platform for the obstacle detection sensor array. This approach eliminates the need for complex gimbals and/or shock suppression suspensions for the sensor array.” ([56], p. 3) and “The suspension response is benign enough to eliminate the need for active control of sensors, saving development time and considerable cost.” ([56], p. 15).

Teams 2005-06, 2005-13, and 2005-14 successfully completed the 2005 GCE. Team 2005-20 completed 81.2 miles of the 2005 GCE course, more than the average number of miles completed. Overall, the author considers the prevalence of this strategy among teams which successfully completed the 2005 GCE and Team 2005-20 supports the following key factors:

- Identify the fundamental problem of the Grand Challenge. Select a challenge vehicle platform with capabilities that may be leveraged.

- Leverage the capabilities of the challenge vehicle platform. Use the challenge vehicle suspension to reduce the impact of off-road terrain on computing hardware and sensors.

In addition, the author considers the prevalence of this strategy confirms the effects of experience and sponsorship.

XIV.B.1.c. <u>Reduce the number of obstacle and path detection sensors in use by eliminating other sensors</u>

The author reviewed the published record in an attempt to quantify the number of major obstacle and path detection sensors in use by the teams, in particular sensors which were considered high-quality. See Chapter VI.

The author concluded there was a decrease in the number of teams using other cameras, other LIDAR, and other RADAR from 2004 to 2005 and a decrease in the number of sensors in use by teams which participated in the 2004 and 2005 GCE. The author considers the reduction in the number of sensors in use due to the elimination of other sensors an example of reducing complexity. See paragraph VI.D.1.

XIV.B.2. Leverage existing COTS components

XIV.B.2.a. <u>Challenge vehicle controls</u>

All teams referred to actuation of challenge vehicle steering, throttle, brake, and transmission controls. In general, teams either independently implemented challenge vehicle controls or integrated COTS controls.

Due to the effect of experience, the author does not consider the integration of COTS challenge vehicle controls by teams with prior experience to have been a key factor for those teams. The author considers it likely teams with prior experience also had experience independently implementing challenge vehicle controls and were able to accomplish this with minimal impact on development of the challenge vehicle, for various reasons. Teams with prior experience included Teams 2004-04 and 2005-02, 2004-10 and 2005-13, 2005-14, 2005-16, and 2004-23 and 2005-21.

Although some teams with significant sponsorship also independently implemented challenge vehicle controls, this was generally required by team selection of challenge vehicle platform. For example:

- Eleven teams participating in the 2004 QID or GCE reported moderate or extensive corporate or academic sponsorship. See Table LXVI. Eight of 11 teams selected a commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform. See Table XV. The author considers it likely integrated COTS controls for these vehicles did not exist, requiring teams to independently implement challenge vehicle controls. Of the remaining three teams: Team 2004-04 selected a commercially-available SUV but had prior experience; Team 2004-09 selected a commercially-available SUV and integrated COTS controls; and Team 2004-17 selected a commercially-available SUV and independently implemented controls.

- Seventeen teams participating in the 2005 GCE reported moderate or extensive corporate or academic sponsorship. See Table LXVII. Ten of 17 teams selected a commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform. See Table XVI. The author considers it likely integrated COTS controls for these vehicles did not exist, necessitating team development of a challenge vehicle control solution.

  Of the remaining seven teams:

  Teams 2005-06, 2005-14, and 2005-16 successfully completed the 2005 GCE, with Team 2005-16 placing first. Team 2005-06 selected a commercially-available SUV and integrated COTS controls; Team 2005-14 selected a commercially-available SUV, had prior experience, and independently implemented controls; and Team 2005-16 selected a commercially-available SUV, had prior experience, and integrated COTS controls.

Teams 2005-08, 2005-12, 2005-18 completed 14.0, 9.5, and 8.0 miles of the 2005 GCE course, respectively. Team 2005-08 selected a commercially-available truck and independently implemented controls; Team 2005-12 selected a commercially-available truck and independently implemented controls; and Team 2005-18 selected a Ford E-350 Van and independently implemented controls. None of these teams had prior experience.

The author is not attempting to imply causation, i.e., that independently implementing controls *caused* Teams 2005-08, 2005-12, and 2005-18 to complete less than the average number of miles of the 2005 GCE course completed, or that integrated COTS controls *caused* Teams 2005-06 and 2005-16 to successfully complete the 2005 GCE. However, the author considers the performance of Teams 2005-06, 2005-08, 2005-12, 2005-14, 2005-16, and 2005-18 to support a conclusion that teams which implemented key factors were more successful.

Team 2005-09 completed 0.7 miles of the 2005 GCE course, the least number of miles of any team which participated in the 2005 GCE. Team 2005-09 selected a commercially-available SUV and integrated COTS controls. Team 2005-09 had no prior experience. Team 2005-09 attributed the cause of their failure to complete the 2005 GCE to errors in obstacle detection. See paragraph XIII.B.5. However, the author concluded the ultimate cause may have been a lack of available resources, specifically time in which to perform adequate test and evaluation of the team challenge vehicle. See paragraph XIV.D.1.

The author considers the use of COTS components a key factor in teams with no prior experience because it reduced complexity and allowed the teams to focus on the fundamental problem in the limited time available to develop a challenge vehicle. The author proposes some teams with no prior experience which independently implemented challenge vehicle controls completed less miles of the 2004 or 2005 GCE course because limited sponsorship restricted the ability of the teams to effectively make use of COTS components, or because teams, correctly or not, determined that independently implementing challenge vehicle controls offered advantages or could be accomplished at minimal cost in terms of team resources.

In addition, the use of COTS components eliminated the need to control the challenge vehicle using actuators, linkages, and other physical components which were a potential cause of failure, and leveraged test and evaluation performed by the manufacturer to ensure the reliability of the component, eliminating the need to divert team resources to perform adequate test and evaluation for the components.

The author made no effort to determine which of the potential rationales, or indeed what other rationale, may have resulted in team decisions to independently implement challenge vehicle controls.

Team descriptions of integrated COTS controls are included herein. The author concluded all other teams independently implemented challenge vehicle controls. Those descriptions were frequently detailed, and are not included herein. In cases where it was unclear, the author attempted to provide enough justification to support his conclusion.

Overall, integrated COTS controls were in use by four teams which participated in the 2004 or 2005 GCE: Teams 2004-09, 2005-06, 2005-09, and 2005-16. Teams 2004-09 and 2005-09 were teams with moderate corporate sponsorship, but no prior experience. Teams 2005-06 and 2005-16 successfully completed the 2005 GCE, with Team 2005-16 placing first. Team 2005-06 had no prior experience and moderate corporate sponsorship. Team 2005-16 had prior experience, moderate corporate sponsorship, and extensive academic sponsorship. None of these teams participated in both the 2004 and 2005 GCE.

The author considers team selection of commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform, and the resulting lack of availability of integrated COTS controls to be a potential limitation of those platforms. Also, the author proposes selection of commercially-available ATV by some teams may have been influenced by lack of sponsorship or resource allocation decisions, and questions whether it was appropriate for DARPA to allow teams with limited sponsorship to participate in the Grand Challenge, or to encourage participation by teams that could not field a vehicle capable of replacing a manned ground vehicle.

- Team 2004-02

Team 2004-02 stated: "The steering wheel is actuated by means of a DC electric servo motor system..."; "[The Electronic Mobility Controls (EMC) Electric Gas Brake (EGB-IIF) unit] is commercial off-the-shelf, installed according to manufacturer's specifications."; and "The shifting is controlled by means of a linear actuator." ([9], p. 4). Although the EMC Electric Gas Brake in use by Team 2004-02 was a COTS component, the author concluded Team 2004-02 independently implemented challenge vehicle controls.

- Team 2004-09

Team 2004-09 stated: “Automation of the vehicle will be accomplished with a subsystem developed by Electronic Mobility Controls LLC...” and “The control of vehicle functions, such as acceleration, braking, and steering, will be performed by a driving control system based on the Advanced Electronic Vehicle Interface Technology (AEVIT) system from Electronic Mobility Controls (EMC) LLC, which modifies the steering wheel, brake and accelerator pedals with commercially available controls.” ([38], p. 2).

- Team 2005-01

Team 2005-01 stated: “The steering wheel is actuated by means of a DC electric servo motor system...”; “[The Electronic Mobility Controls (EMC) Electric Gas Brake (EGB-IIF) unit] is commercial off-the-shelf, installed according to manufacturer’s specifications.”; and “The shifting is controlled by means of a linear actuator.” ([10], pp. 10 - 11). Although the EMC Electric Gas Brake in use by Team 2005-01 was a COTS component, the author concluded Team 2005-01 independently implemented challenge vehicle controls.

- Team 2005-02

Team 2005-02 stated: “The automation of the vehicle, to include power system design and actuation, was headed by personnel of Eigenpoint, Inc.” ([167], p. 3). Team 2005-02 reported the team was a collaboration of several groups, including Eigenpoint. Although Eigenpoint claimed to have over a decade of experience in “robotic and automation systems”, and (as of 2004) to be “applying our knowledge towards developing our own products”, the “Products” page of the Eigenpoint website was (as of 2010) “under construction” ([246]). As a result, the author concluded Eigenpoint did not offer COTS challenge vehicle controls at the time of the 2005 GCE, and that Team 2005-02 independently implemented challenge vehicle controls.

- Team 2005-04

Team 2005-04 stated: “Drive by wire capability was added to the vehicle so that computer control was possible for throttle, brake, steering control, and transmission gear.” ([169], p. 3), but did not affirmatively state integrated COTS controls were in use by the team. In addition, Team 2005-04 selected a commercially-available ATV as challenge vehicle platform. See Table XVI. The author concluded Team 2005-04 independently implemented challenge vehicle controls.

- Team 2005-06

Team 2005-06 stated: “[Team 2005-06] installed an AEVIT 'drive-by-wire' system from Electronic Mobility Controls (EMC) to physically control the car. The AEVIT system uses redundant servos and motors to turn the steering wheel, switch gears, apply throttle, and apply brake. A primary reason that this system was chosen was because it has a proven safety record in the automobile industry due to its use of redundant hardware. One of [Team 2005-06's] primary goals in all of their designs is redundancy, and the AEVIT system satisfies this goal... This level of reliability in the physical vehicle controls has allowed the team's efforts to be spent on other critical projects rather than wasting time solving vehicle control problems." ([172], p. 4).

- Team 2005-09

Team 2005-09 stated: "Immediately after purchase, [the challenge vehicle] was modified by EMC (Electronic Mobility Controls Corp) to provide a drive-by-wire capability. This included modifications to both the transmission and steering column... By using EMC, the [challenge vehicle] has a robust drive-by-wire capability that leverages years of investment and experience." ([175], p. 3).

Team 2005-09 also stated team selection of challenge vehicle platform was influenced by the availability of integrated COTS controls: "Another consideration that influenced our decision is that Ford vehicles are well understood by Electronic Mobility Controls Corp (EMC), the vendor that provided our drive-by-wire capability." ([175], p. 2). The author proposes this may also have influenced Team 2005-06 selection of a Ford Escape Hybrid as challenge vehicle platform.

- Team 2005-10

Team 2005-10 stated: "The process of designing and assembling the drive-by-wire systems... was rather straightforward." ([176], p. 6). Team 2005-10 did not report the results of formal or informal failure analysis via the Journal of Field Robotics. As a result, the author did not include Team 2005-10 in the summary results presented in paragraph XIII.C. However, Team 2005-10 later stated: "...around mile marker 23, the servo motor that we installed a year ago to actuate the throttle suddenly failed, and the on board computer had no way to control the throttle." ([247]). The author considers this supports an assertion that the use of COTS components leverages test and evaluation performed by the manufacturer to ensure the reliability of the component. No team which used integrated COTS controls reported a similar failure.

- Team 2005-16

Team 2005-16 selected a 2004 Volkswagen Touareg R5 as challenge vehicle platform. See Table XVI. Team 2005-16 stated: "The Volkswagen Touareg R5 is natively throttle and brake-by-wire. A custom interface to the throttle and braking system enables [the challenge vehicle's] computers to actuate both of these systems. An additional DC motor attached to the steering column provides the vehicle with a steer-by-wire capability." ([195], p. 4). Team 2005-16 also stated: "The team is comprised of four major groups: The *Vehicle Group* oversees all modifications and component developments related to the core vehicle. This includes the drive-by-wire systems... The group is led by researchers from Volkswagen of America's Electronic Research Lab." ([195], p. 3). Because the steer-by-wire capability was added by the OEM, the author concluded Team 2005-16 integrated COTS controls were essentially OEM controls for the vehicle selected as challenge vehicle platform.

The author considers the use of OEM controls the best possible outcome for teams participating in the 2004 or 2005 GCE. OEM controls were in use by Team 2005-16 only.

XIV.B.2.b. Navigation sensor integration

Several teams independently implemented an other sensor fusion strategy. See Chapter VII. Teams which did not implement their own navigation sensor integration solution were able to leverage an existing COTS component. Overall, the author concluded the use of a COTS component to integrate navigation sensors was an example of reducing complexity by leveraging existing COTS components.

XIV.B.2.c. High-quality sensors

The author reviewed the published record in an attempt to quantify the number of major obstacle and path detection sensors in use by the teams, in particular sensors which were considered high-quality. See Chapter VI.

The author concluded there was an increase in the number of high-quality obstacle and path detection sensors in use. The author considers the increase in the number of high-quality obstacle and path detection sensors in use an example of reducing complexity by leveraging existing COTS components. See paragraph VI.D.1.

XIV.B.3. Object classification or identification

Several teams which participated in the 2004 QID or GCE explicitly stated the challenge vehicle controlling intelligence did not classify or identify objects: Teams 2004-06, 2004-09, 2004-12, and 2004-23. However, teams which participated in the 2004 QID or GCE or 2005 GCE and which reported the challenge vehicle controlling intelligence classified or identified objects reported objects were classified on the basis of characteristics such as: "passable" or "impassable"; "temporary" or "permanent"; "hard", "medium", or "soft"; "size"; and "location". For example, Team 2004-21 stated: "For the moment, we do not plan on having the system classify sensed objects other than as an obstruction." ([155], p. 5). In general, objects were not classified as "gate", "fence", or "guardrail".

The author considers this evidence supports an assertion the teams were making an active effort to reduce complexity by providing the controlling intelligence with the minimal information needed for obstacle avoidance. However, an inability to effectively classify obstacles as “passable” was directly implicated in the failure of several teams to complete the 2004 or 2005 GCE, including several teams which explicitly stated the challenge vehicle controlling intelligence did not classify or identify objects. For example:

- DARPA reported the Team 2004-06 challenge vehicle “was paused to allow a wrecker to get through, and, upon resuming motion, vehicle was hung up on a football-sized rock.” ([30]). The author considers this an example of the challenge vehicle controlling intelligence incorrectly classifying an obstacle as “passable”.

- DARPA reported the Team 2004-23 challenge vehicle repeatedly “sensed some bushes near the road, backed up and corrected itself. At mile 1.2, it was not able to proceed further.” ([30]). The author considers this an example of the challenge vehicle controlling intelligence incorrectly classifying an obstacle as “impassable”.

- Team 2005-09 failed to complete the 2005 GCE, and stated the challenge vehicle detected occasional dust clouds as transient obstacles, which ultimately caused the challenge vehicle to veer off course where it was unable to continue because “the lasers could not differentiate between weeds and large rocks”. See paragraph XIII.B.5. The author considers this an example of the challenge vehicle controlling intelligence incorrectly classifying an obstacle as “impassable”.

XIV.B.4. Miscellaneous observations

In addition to the specific observations documented above, which were of particular interest to the author, the author noted the following miscellaneous observations, which support a conclusion that teams were making an active effort to reduce complexity, in some cases based on experience gained from participation in the 2004 GCE.

- Team 2004-11

Team 2004-11 stated: “There are no other 'typical' engine status sensors on the vehicle, as they would have little use. In a real-world application this would not be the case, but within the limits of this event it is advantageous to keep things as simple as possible.” ([127], pp. 6 - 7).

However, Team 2004-11's decision to “keep things as simple as possible” may have been counterproductive. Following a DARPA site visit prior to the 2005 NQE, Team 2004-11 stated: “Our entry never made it into the semi-finals of qualifying for the '05 event, even though we did turn out a few good autonomous runs during our Site Visit Qualifying. Our demise may have been the fact that we had no obstacle avoidance systems running that day. In an attempt to keep things simple, it was decided to run only sonar that day, since at the time our other sensors only came on line at speeds higher than 15 mph. Early that morning while doing practice runs for the Site Visit, the sonar processor dumped its program, rendering the three sensors useless. With no programming board on site, and no time to run and get one, we ended up 'flying blind' for the day.” ([126]).

- Team 2004-18

Team 2004-18 stated: “The design utilizes standard off-the-shelf sensors and hardware.” ([48], p. 1).

- Team 2004-21

Team 2004-21 repeatedly expressed a desire to “keep things simple”: “We prefer to keep things as simple as possible.” ([155], p. 5), “We want to keep things simple..” ([155], p. 6) and “This makes our design simple...” ([155], p. 8).

However, Team 2004-21's desire to “keep things simple” was at odds with the team's identification of the fundamental problem of the Grand Challenge. Team 2004-21 reported implementing a programming language, a compact standard and solar charging system, and a “hybrid navigation system unlike anything used before”. See paragraph XIV.A.6.

- Team 2005-04

Team 2005-04 stated: “Lessons learned with the [Team 2004-23] experience were taken to heart and a simpler, cleaner configuration and interprocessor data communication mechanism was created.” ([169], p. 5).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “In meeting the Grand Challenge, two principles emerged as the keys to robustness and success: Keep the components simple...” ([24], p. 468).

- Team 2005-15

Team 2005-15 stated: “The emphasis in designing our system architecture was on simplicity and modularity: failure of one component was not to affect the functionality of the main components.” ([53], p. 5).

- Team 2005-16

Team 2005-16 stated: “[Team 2005-16] leverages proven commercial off-the-shelf vehicles...” ([195], p. 2).

XIV.C. Reliability and redundancy

Several teams selected reliable components, including a more recent model year vehicle for challenge vehicle platform, increased redundancy in key components where possible, and took proactive measures to ensure reliability, such as shock isolation. This was limited, to a certain extent, by the effects of experience and sponsorship and resource allocation decisions. For example:

XIV.C.1. Select reliable components

- Team 2004-04

Team 2004-04 stated: "[The Team 2004-04 challenge vehicle] also benefits greatly from the unique partnership with Autonomous Solutions, Inc. (ASI) and their similar background in autonomous systems development... The software components (Primitive Driver, Path Planner, Path Manager, Planning Element Knowledge Store, Reactive Planner) and vehicle conversion that ASI is in charge of have been implemented, tested, and proven to be safe and reliable on numerous vehicles currently in use around the world." ([44], p. 11).

- Team 2004-08

Team 2004-08 stated: "We chose the 1330 series because of its 'sealed and pressurized environmental enclosure [which] provides maximum protection against rain, snow, dust, ...' This device is also designed to withstand high shock and vibration." ([76], p. 4).

- Team 2004-09

Team 2004-09 stated: "...mission-critical operating system, software, and parameters may be stored on highly reliable solid-state media that is relatively immune to high temperatures or other shock conditions." ([47], p. 3).

- Team 2004-11

Team 2004-11 stated: "We decided to do away with the long-range radar after we found it to be hard to focus and unreliable in the returns it provided. We opted instead for a fixed long-range laser rangefinder which is much more reliable, and precise." ([127], p. 4) and "As we mentioned earlier, after numerous tests and attempts to calibrate the radar for our application, we opted for a more reliable laser rangefinder to take its place." ([127], p. 8).

Team 2004-11 also stated: "We have tested the sonar set and found it to be reliable and functional for detecting objects at the 50-foot range." ([127], p. 8).

- Team 2004-17

Team 2004-17 stated: "We used an off-the-shelf system (AutoTap) to read data from the On-Board Diagnostic (OBD) system that is part of all 1996 and later vehicles. We found the data from OBD-II to be less than reliable." ([142], p. 11).

- Team 2005-01

Team 2005-01 stated: "Five Dell Servers have proven reliability while working in the field." and "[The challenge vehicle's] Artificial Intelligence software is written in Linux [*sic*], which is know for its reliability..." ([10], p. 5).

- Team 2005-03

Team 2005-03 stated: "DSP chips have been in use for decades controlling mission-critical systems for commercial and government applications so the reliability should be excellent." ([33], p. 4) and "All computer processing and vehicle navigation is based on highly reliable DSP chips with proven field reliability in thousands of products worldwide." ([33], p. 12). Team 2005-03 also stated: "This vehicle was chosen for its reliability..." ([33], p. 4).

- Team 2005-05

Team 2005-05 stated: "For the 2005 Grand Challenge, we decided to ... prepare a similar second vehicle for use in the Grand Challenge Event. [The challenge vehicle] is based on a 2005 Dodge Ram 2500. We chose a new model year truck, as opposed to another 1994 model like [the Team 2004-07 challenge vehicle], in order to get better mechanical reliability." ([34], p. 2).

- Team 2005-06

Integrated COTS controls were in use by Team 2005-06. See paragraph XIV.B.2.a. Team 2005-06 stated: "This level of reliability in the physical vehicle controls has allowed the team's efforts to be spent on other critical projects rather than wasting time solving vehicle control problems." ([172], p. 4).

- Team 2005-09

Team 2005-09 stated: "Additionally, a set of four off-road Super Swamper tires was also added to increase reliability in rugged terrain." ([175], p. 3).

- Team 2005-17

Team 2005-17 stated: "The student crafted cage using aluminum rods purchased from a local hardware store has been replaced by a student-designed but professionally manufactured aluminum structure. A hand rigged case that served as a rack is now replaced by a MIL-spec rack manufactured by Hardigg." ([140], p. 2).

- Team 2005-21

Team 2005-21 stated: "The hardware was selected specifically for the DARPA Challenge race conditions with consideration for withstanding the hot desert conditions and the ruggedness required for off-road high and low frequency vibration." ([160], p. 3).

XIV.C.2. Increase redundancy in key components

Several teams described strategies for increasing the redundancy of key components. The author notes that teams variously identified "key components". Common examples include redundant challenge vehicle alternators, GPS sensors, challenge vehicle brakes, and computing hardware.

Several teams reported a sensor or type of sensor was "redundant" in the sense that it provided obstacle and path detection information in the event another sensor failed, for example Teams 2005-08 and 2005-15. The author considers this to be an example of functional redundancy, not component redundancy. Although several teams reported functional redundancy, those descriptions are not included herein.

- Team 2004-01

Team 2004-01 stated: "Braking will be accomplished using standard automotive 4 wheel hydraulic brakes actuated by a double redundant pneumatic system." ([8], p. 1).

Team 2004-01 also stated: "Redundant hard drives provide storage for data." ([8], p. 2).

- Team 2004-02

Team 2004-02 stated: "Two (2) independent alternators operating redundantly will charge the batteries." ([9], p. 4).

- Team 2004-07

In describing a "Redundant Pneumatic Braking System" Team 2004-07 stated: "There will be two independent pneumatic braking systems." ([46], p. 2).

- Team 2005-01

Team 2005-01 stated: “Two (2) independent alternators operating redundantly will charge the batteries.” ([10], p. 4).

- Team 2005-02

Team 2005-02 stated: “The power system consists of two independent 140 A 28 V alternator systems... Each alternator drives a 2400 W continuous, 4800 W peak inverter and is backed up by four deep-cell batteries. Each alternator feeds one of two automatic transfer switches (ATS). The output of one ATS drives the computers and electronics, while the other drives the actuators and a 3/4 ton (~ 1 kW cooling) air conditioner. Should either the alternator or battery system fail, the entire load automatically switches to the other alternator or battery system. The total system power requirement is approximately 2200 W, so the power system is totally redundant.” ([50], p. 604).

- Team 2005-03

Team 2005-03 stated: “Dual GPS receivers are used, both to establish direction at rest and to provide redundancy.” and “The third gyro in the 6-axis system is used as a redundant backup for the FOG gyro.” ([33], p. 7).

- Team 2005-05

Team 2005-05 stated: “For the 2005 Grand Challenge, we decided to ... prepare a similar second vehicle for use in the Grand Challenge Event. ...we wanted a second vehicle for redundancy (we were aware that several teams suffered serious vehicle accidents in the days leading up to the 2004 Grand Challenge)...” ([34], pp. 2 - 3).

Team 2005-05 also stated: “For development purposes, [the challenge vehicles] are run by laptop computers... Any of the laptops can be inserted into either of [the challenge vehicles] and be used as the controlling computer. ...the system is highly redundant, so that if the laptop driving the vehicle were accidentally destroyed by an electrical short (as happened immediately prior to our DARPA Grand Challenge Site Visit) it could immediately be replaced by any of the other team members’ laptops. The alternative approach of keeping a privileged computer or set of computers permanently mounted in the vehicles would, we think, reduce redundancy...” ([34], p. 3).

- Team 2005-06

Team 2005-06 stated: “[Team 2005-06] installed an AEVIT 'drive-by-wire' system from Electronic Mobility Controls (EMC) to physically control the car. The AEVIT system uses redundant servos and motors to turn the steering wheel, switch gears, apply throttle, and apply brake. A primary reason that this system was chosen was because it has a proven safety record in the automobile industry due to its use of redundant hardware. One of [Team 2005-06's] primary goals in all of their designs is redundancy, and the AEVIT system satisfies this goal." ([172], p. 4).

Team 2005-06 stated: "...[Team 2005-06] chose to use several 1.42 Gigahertz Apple Mac Mini computers to host the path-planning software. These Mac Minis perform all of the path calculations in a redundant cluster. This ensures that the path planning software does not become a single point of failure." ([172], p. 7).

Team 2005-06 stated: "[Team 2005-06] considers the GPS its most important piece of hardware. As a result of this, it has installed two Oxford RT3000 GPS units on its vehicle. Rather than try to integrate the data from both units at the same time, [Team 2005-06] instead chose to use the two units in a primary/secondary role. Both units are always active, but if one unit stops sending data for some reason, the other unit immediately takes over and becomes the primary unit. This configuration ensures that [Team 2005-06] will have accurate GPS information at all times." ([172], p. 9).

- Team 2005-11

Team 2005-11 stated: "Hardware and software have been designed to minimize the impact of temporary failed components. However, limited redundancy in components means that permanent outages of sensors will have a detrimental effect on [the challenge vehicle's] performance." ([182], p. 7).

- Team 2005-17

Team 2005-17 stated: "A single, garden variety mother board is replaced by two Dell Power Edge 750 computers and two mini-ITX boards." and "The single Honda EU2000 generator now shares a berth with another identical generator." ([140], p. 2).

- Team 2005-20

Team 2005-20 stated: "The second GPS unit also provides redundancy in case of failure of the primary GPS or at times when the primary GPS antenna is experiencing high levels of blockage." ([56], p. 9).

XIV.C.3. Take proactive measures to ensure reliability

Several teams reported proactive measures other than test and evaluation in use by the team to ensure reliability, such as shock isolation or sensor stabilization. For example:

- Team 2004-03

Team 2004-03 stated: "The cameras are mounted on a gimbaled gyro-stabilized sensor mount directly above the front wheel." ([92], p. 5).

- Team 2004-04

Team 2004-04 stated: “The solid-state flash cards are used to increase vehicle ruggedness by eliminating the poor shock and vibration tolerance of ordinary hard drives.” ([44], p. 3).

- Team 2004-07

Team 2004-07 stated: “On the roof is another forward Sony DFW-VL500, passively stabilized by a Kenyon Labs KS-8 gyrostabilizer.” ([46], p. 7).

- Team 2004-09

Team 2004-09 stated: “A passive platform will be designed utilizing materials developed to minimize mechanical shock to the processors and sensor mounts.”, “...the mission-critical operating system, software, and parameters may be stored on highly reliable solid-state media that is relatively immune to high temperatures or other shock conditions.”, “Shock mounts and an isolation platform will be used to enhance the survivability of these components.”, and “Except as noted, all units are general-purpose processor boards, running Linux, in an air-cooled shock-mounted rack.” ([47], p. 3). Team 2004-09 also stated: “The video camera and laser will be shock-mounted on the dashboard of the vehicle.” and “We will use a rapid shutter speed of 1/8000 sec. to minimize blurring. We will mount the camera and other sensors on a platform designed to absorb shock.” ([47], p. 7).

- Team 2004-10

Team 2004-10 stated: “E-box shock isolation system was designed and implemented, based on analyzed and measured dynamic inertial data.” ([77], p. 6). In addition, Team 2004-10 reported several sensors were stabilized ([77], p. 4).

- Teams 2004-13 and 2004-14

Teams 2004-13 and 2004-14 stated: “The RADAR will be used to supplement the obstacle detection capability of the LADAR system in situations where visibility is limited by dust, fog, or rain. It will also be relied upon when the LADAR system is 'dazzled' by the sun.” ([232], p. 3 and [132], p. 4).

Teams 2004-13 and 2004-14 also stated: “There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one. Use of these sensors will assure that the vehicle can sense nearby objects, even when bright sunlight or obscurants such as fog or dust temporarily disable or confuse the optical sensors.” ([232], p. 4 and [132], p. 4).

- Team 2004-17

In response to 2004 SQ 2.a (see Table XXII), Team 2004-17 described extensive component test and evaluation of the challenge vehicle platform and sensors in use by the team. However, Team 2004-17 also reported the results of reliability testing performed by the team. When describing a "Hard drive survivability" test, Team 2004-17 stated: "The purpose of this test was to determine what hard drive mounting methods, if any, would protect them from damage while driving off-road. Computers with spinning hard drives were installed in the back of the stock 1996 Chevy Tahoe. 6 hard drives were tested. Two were installed via a standard mount, two were encased in foam rubber, one was suspended by an 8-point spring mount, and one was mounted on rubber washers. The only disk to fail outright was the spring-mounted drive." ([142], p. 11). When describing "system tests" which were "performed in the field", Team 2004-17 stated: "some generator issues were identified and resolved" and "More generator issues were discovered and resolved. Computing integration issues (software bugs, processor speeds) were discovered and resolved." ([142], pp. 10 - 11).

- Team 2004-24

Team 2004-24 stated: "...[the challenge vehicle] contains is [*sic*] a boom and platform that houses the most shock sensitive equipment." ([161], p. 5).

- Team 2005-04

Team 2005-04 stated: "The remaining electronics were mounted in a shock-mounted metal enclosure... for protection from... terrain induced vibrations affixed to the cargo bed of the vehicle." ([169], p. 3).

- Team 2005-06

Team 2005-06 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. In addition, Team 2005-06 stated: "In order to ensure that the best computing hardware was chosen, [Team 2005-06] investigated the leading computing hardware used by several different industries. The marine industry offered a ready made system that included protection from excessive shock... This system... hosts all of the main computing functions, such as sensor communication, vehicle controls, and artificial intelligence." ([172], p. 7).

- Team 2005-08

Team 2005-08 stated: "The environmental enclosure is supported on each corner using Lord Heavy Duty Plateform shock isolation mounts." ([173], p. 5).

- Team 2005-10

Team 2005-10 stated: “To date, the only component that has failed as the result of this testing was the vibration mounts for the lower SICK LIDAR. These were replaced with a more robust design.” ([176], p. 6).

- Team 2005-11

Team 2005-11 stated: “Attached to [the challenge vehicle's] chassis frame is a stressed skin aluminum body which houses the batteries, computer and control electronics. The central portion of this aluminum body is shock mounted... to protect sensitive components from damage.” ([182], pp. 5 - 6).

- Team 2005-12

Team 2005-12 stated: “The software framework was designed with the goals of flexibility, productivity, and reliability in mind. The system is composed of a number of standalone components that interact with each other through direct communication as well as event-based signaling. In addition to significantly reducing complexity, this component-based and event-based architecture makes system monitoring very easy, as a great deal of system reliability is achieved simply through the addition of another 'watchdog' component, whose sole job is to monitor the functioning of the other system components.” ([185], pp. 4 - 5).

- Team 2005-13

Team 2005-13 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. In addition, Team 2005-13 stated: “A custom aluminum body and a cooled, shock- isolated electronics bay replaced the crew compartment body panels, doors, seats and windshield.” ([11], p. 2). Team 2005-13 also stated: “An actuated three-axis gimbal... stabilizes the long range single line LIDAR...” ([11], p. 7).

- Team 2005-14

Team 2005-14 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. In addition, Team 2005-14 stated: “[The challenge vehicle's] electronics enclosure sits on a semi-active modified Stewart Platform.” ([12], p. 3). Team 2005-14 also stated: “An actuated three-axis gimbal... stabilizes the long range single line LIDAR...” ([12], p. 7).

- Team 2005-15

Team 2005-15 stated: “The key to the Grand Challenge was not necessarily the incredibly accurate sensing technology or immense amounts of computing power. [The challenge vehicle] was able to detect and avoid the same obstacles as teams with twice the number of sensors and considerably more than twice the computing power. With intelligent yet efficient algorithms and a few key sensors, these hurdles could be overcome. The failure that finally disabled [the challenge vehicle] was a simple hardware connection malfunction. More time needed to be spent by the team to harden the vehicle. [The challenge vehicle's] concept was validated by its showing in the Grand Challenge; with more time, the realization of its potential would also have been reached." ([133], p. 596).

- Team 2005-17

In describing a proprietary terrain modeling and obstacle detection algorithm, Team 2005-17 stated: "A special property of the algorithm... is that it does not require that the sensors be stabilized to reduce the shocks and vibrations they experience. This reduces the cost of developing the system since we do not need to use a gimble [*sic*] to stabilize the sensors." ([140], p. 9).

- Team 2005-18

Team 2005-18 stated: "The servers themselves are housed in a shock-isolated, climate-controlled box fitted with mil-spec connectors." ([197], p. 7).

- Team 2005-19

Team 2005-19 stated: "The rough desert terrain can easily damage sensitive electronics required to operate a vehicle autonomously for extended periods of time. To prevent damage, the computers are stored in a pair of opposite-facing rack mounts situated across the back seat of [the challenge vehicle]... The rack mount is vibration isolated from the floor of the vehicle by a six spring/damper suspension system. The suspension system is designed to constrain all six degrees of freedom of the computer rack and to keep displacement and force transmission low at the frequencies experienced by normal driving..." ([55], pp. 7 - 8).

- Team 2005-20

Team 2005-20 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. However, Team 2005-20 reported "small variations in the car's pose can result in very large errors in the positions of distant obstacles, even if inertial data is considered." ([56], pp. 6 - 7).

In addition to the examples cited above, several teams variously referred to shock-mounted, shock-resistant, vibration-resistant[32], or stabilized computing hardware or sensors: Teams 2004-02, 2004-03, 2004-04, 2004-07, 2004-10, 2004-16, 2004-22, 2004-25, 2005-01, 2005-02, 2005-03, 2005-09, 2005-13, 2005-14, 2005-16, 2005-18, 2005-21, 2005-22, 2005-23.

XIV.C.4. Miscellaneous observations

In addition to the specific observations documented above, which were of particular interest to the author, the author noted the following miscellaneous observations, which support a conclusion that teams were making an active effort to increase reliability and redundancy, in some cases based on experience gained from participation in the 2004 GCE.

- Team 2005-03

Team 2005-03 stated: "We have applied what we learned in the first race to harden our vehicle in the areas of tires, wiring, mounting hardware, and field-testing." ([33], p. 12).

- Team 2005-19

Team 2005-19 stated: "Although no team came close to finishing the course last year, many lessons were learned from the successes and failures of last year's entrants, and unexpected problems became apparent. In entering the 2005 Grand Challenge, we have the added benefit of being able to observe these deficiencies so that we may ensure that our vehicle will not be defeated by the same design flaws." ([55], p. 2).

Ironically, Team 2005-19 was one of five teams which failed to complete the 2005 GCE due to GPS sensor failure, which was a preventable system integration failure with adequate test and evaluation. See paragraph XIII.B.12.

XIV.D. Test and evaluation

XIV.D.1. Perform adequate test and evaluation

Several teams reported a lack of time prevented them from fully implementing their challenge vehicle[33] or reported details which support a conclusion that the team was unable to complete planned test and evaluation[34]:

- Team 2004-04

Via their response to 2004 SQ 2.b (see Table XXII), Team 2004-04 described an extensive series of planned tests, and stated: "Four different integration tests will be conducted on [the challenge vehicle]." ([44], p. 12). The Team 2004-04 technical proposal was dated February 27, 2004, approximately two weeks prior to the 2004 GCE.

- Team 2004-07

In response to 2004 SQ 1.a.3 (see Table XXII), Team 2004-07 stated: "Once we have achieved reasonable forward driving, we will consider adding a reverse driving capability and submit an addendum to this report if necessary." ([46], p. 3).

- Team 2004-09

Team 2004-09 stated: "Sensors that facilitate moving in reverse with a maximum range of 6 feet ... may be used to assist [the challenge vehicle] should there be a situation where it must back up. However, in consideration of the timeline and final simplicity of our design, these sensors may not be used in the initial version of the vehicle." ([47], p. 7).

- Team 2004-11

In response to 2004 SQ 1.h.2 (see Table XXII), when describing wireless signals received by the challenge vehicle, Team 2004-11 stated: "We regret that time did not allow us to pursue another idea past a few initial experiments." ([127], p. 8), but reported no additional information.

- Team 2004-14

Team 2004-14 stated: "...the biggest challenge was to work against the clock. Time was critical, and for a team like us who was working not during the day-time job but during nights and weekends, this proved to be a big issue." ([248])

- Team 2005-15

Team 2005-15 stated: "[Team 2005-15], along with Seibersdorf Research, managed to build a strong contender for the DARPA Grand Challenge 2005. A team of volunteer engineers with limited resources managed to stay competitive among teams with more time, money, and resources." ([133], p. 596).

- Team 2005-17

Team 2005-17 stated ([196], pp. 576 - 577):

> Our experience suggests that field testing is one of the most expensive parts of developing an AGV. To field test, one must have a fully operational vehicle, a field for testing it, correct weather conditions, and a significant amount of staff. Unless the procedures for bringing the vehicle to the field are very well-defined, small issues, such as insufficient gas in the generator, can consume significant time.
>
> Having a fully operational vehicle is no small requirement, given that an AGV has linear dependencies between the automotive, the electromechanical components, the electrical, electronics, sensors, and

the software. Failure in any one of the components can hold back the testing.

In general, teams which participated in the 2004 or 2005 GCE reported “planned” or “previous” (herein “planned”) and "completed" or "past" (herein "completed") test and evaluation in response to 2004 SQ 2.a and 2.b (see Table XXII) and 2005 SQ 2.5.1 and 2.5.2 (see Table XXIII).

Because the sections of team technical proposals which reported planned and completed test and evaluation were extensive, they are not included herein. The reader is directed to the team technical proposals, a complete list of which is available from the Archived Grand Challenge 2004 and 2005 websites ([17] and [19]) or in the “References” section of this technical report.

The author established the following categories of test and evaluation considered to be essential to the development of a challenge vehicle: “component”, “waypoint following and path detection”, and “obstacle detection and avoidance”. The author reviewed planned and completed test and evaluation reported by team technical proposals for key words associated with the categories of testing considered to be essential.

- Component. The author considered descriptions of sensor evaluation, including GPS sensor reception, challenge vehicle handling characteristics, and drive-by-wire implementation to be typical. In addition, because it is unclear if it was necessary or even desirable (see Chapter XII.) to increase waypoint density to successfully complete the 2004 or 2005 GCE, the author considers the development of “path planning” or “route planning” algorithms to be in the category "component", not "navigation".

- Waypoint following and path detection. The author considered the following key words to be typical: “navigation”, “path following”, “path tracking”, “road following”, “road tracking”, “route finding”, “route following”, “waypoint following”, and “waypoint navigation”.

- Obstacle detection and avoidance. The author considered the following key words to be typical: “obstacle detection”, “object detection”, “obstacle avoidance”, and “point cloud”.

The author established the following levels of testing: Incomplete (“I”), Partially completed (“P”), or Significantly completed (“S”).

Test and evaluation reported by the teams was considered incomplete only if the team did not report any planned or completed test and evaluation for that category of testing, significantly completed if the technical proposal reported completed planned test and evaluation for that category of testing, and partially completed otherwise. All three categories were considered significantly completed if the team reported test and evaluation of a fully autonomous challenge vehicle, for example, by number of autonomous miles completed or “endurance test”, no matter how many autonomous miles were completed.

The initial attempt by the author to determine whether teams which participated in the 2004 QID or GCE, and which reported completed test and evaluation, performed better or completed more miles than teams which only reported planned test and evaluation was unsuccessful for several reasons:

- Two of 25 teams which participated in the 2004 QID or GCE did not respond to either 2004 SQ 2.a or 2.b (see Table XXII): Teams 2004-15 and 2004-24. Team 2004-04 reported no planned or completed component test and evaluation.

- Twenty-two of 22 teams which participated in the 2004 QID or GCE and which responded to 2004 SQ 2.a and 2.b reported partially or significantly completed component test and evaluation.

- Four of 23 teams reported partially completed waypoint following and path detection test and evaluation: Teams 2004-11, 2004-13, 2004-14, and 2004-20.

- Two of 23 teams reported partially completed obstacle detection and avoidance test and evaluation: Teams 2004-11 and 2004-12. One of 22 teams reported significantly completed obstacle detection and avoidance test and evaluation: Team 2004-10.

- Eight of 25 teams submitted revised technical proposals in the two weeks prior to the 2004 GCE. Twelve of 25 teams submitted revised technical proposals in the 30 days prior to the 2004 GCE. Some teams which submitted revised technical proposals did not update their technical proposals to record completed test and evaluation.

- Thirteen of 25 teams did not date or otherwise report the revision of their technical proposals. As a result, it was not possible to determine if these teams submitted revised technical proposals reporting test and evaluation completed since a prior revision.

- Few teams reported the results of their participation in the 2004 GCE. The Team 2005-04 technical proposal ([169]) referenced two papers which reported Team 2004-23[25] results following the 2004 GCE. The Team 2005-06 technical proposal ([172]) referenced a paper which reported Team 2004-23 results following the 2004 GCE. In addition, Team 2005-13 published several papers following the 2004 GCE, some of which are referenced herein as published records. However, no team which participated in both the 2004 and 2005 GCE referenced published results in their 2005 technical proposals, including Team 2005-13.

The initial attempt by the author to determine whether teams which participated in the 2005 GCE, and which reported completed test and evaluation, completed more miles than than teams which only reported planned test and evaluation was unsuccessful for several reasons:

- Four of 22[35] teams which participated in the 2005 GCE reported partially or significantly completed component test and evaluation, incomplete waypoint following and path detection, and incomplete obstacle detection and avoidance test and evaluation: Teams 2005-01, 2005-04, 2005-11, and 2005-15.
- Eighteen of 22 teams reported significantly completed component, waypoint following and path detection, and obstacle detection and avoidance test and evaluation.
- Nine of 22 teams submitted revised technical proposals in the sixty days prior to the 2005 GCE.
- Thirteen of 22 teams did not date or otherwise report the revision of their technical proposals. As a result, it was not possible to determine if these teams submitted revised technical proposals reporting test and evaluation completed since a prior revision.
- Sixteen of 23 teams reported the results of their participation in the 2005 GCE via the Journal of Field Robotics. Seven of 23 teams did not, including several teams which participated in both the 2004 and 2005 GCE.

Overall, the category and level of test and evaluation reported by the teams was exceptionally difficult to quantify. An attempt was made to tabulate results, but the author determined the published record was incomplete, insufficient technical detail was reported by most teams, and assessment of category and level of test and evaluation was too subjective for any comparison to have meaning.

In addition, as noted in paragraph V.E.1.b., the technical proposals submitted to DARPA were of indifferent quality, containing a large number of technical mistakes which rendered meanings unclear. For example:

- Team 2005-01

Team 2005-01 participated in the 2004 GCE as Team 2004-02. Team 2005-01's response to 2005 SQ 2.5.1 does not differ significantly from Team 2004-02's response to 2004 SQ 2.a, including repeated errors such as “ODB-II” for OBD-II and “[The challenge vehicle's] GPS system has been tested for accuracy against other COTS GPS system [*sic*].” ([9], p. 12 and [10], p. 13). In addition, Team 2005-01 reported: “The team continues to do cost analysis of the race use of this information." in reference to OBD-II information and "The LADAR unit has been installed..." ([9], p. 12 and [10], p. 13).

The Team 2005-01 technical proposal is dated August 11, 2005, less than 60 days prior to the 2005 GCE, however Team 2005-01 reported a fully autonomous challenge vehicle: "Extensive testing in the field has led to extensive development of these corner cases." ([10], p. 11).

- Teams 2005-13 and 2005-14

Team 2005-14 stated: "[Team 2005-14] has been testing [the challenge vehicle's] systems and subsystems since it became operational in December of 2003." ([12], p. 15). Team 2005-14 also stated: "[The challenge vehicle's] hardware configuration has been frozen since June 1, 2005. [The challenge vehicle] was assembly complete on July 23, 2005." ([12], p. 5) and "[The challenge vehicle] used this maneuver during the 2004 DARPA Grand Challenge after hitting a large rock." ([12], p. 14).

However, although Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE, neither Team 2005-14 nor the 2005-14 challenge vehicle participated in the 2004 GCE.

The author concluded Teams 2005-13 and 2005-14 revised the same base document to create the technical proposals specific to their team challenge vehicles, and that this may be the reason Team 2005-14 referred to events which occurred during the 2004 GCE despite not having participated in the 2004 GCE.

- Teams 2005-22 and 2005-23

Based on the similarity between their technical proposals, the author concluded Teams 2005-22 and 2005-23 revised the same base document to create the technical proposals specific to their challenge vehicles. The Team 2005-22 technical proposal contains many annotated revisions.

In addition, the Team 2005-22 technical proposal is incomplete, lacking detail reported by the Team 2005-23 technical proposal. For example, Team 2005-22 stated: "It also allowed for testing during conditions where it would normally not be possible, such as at night or times when [*sic*]" ([58], p. 13). The corresponding statement in the Team 2005-23 technical proposal was: "It also allowed for testing during conditions where it would normally not be possible, such as at night or during heavy rain." ([164], p. 12).

As a result, it is unclear if the Team 2005-22 technical proposal represents the final published record of the team prior to the 2005 GCE or if the technical proposal was incomplete, or a work in progress, when it was submitted to DARPA.

In addition, the Team 2005-23 technical proposal contains an extensive passage of almost identically-worded text on pages 6 and 12 which describes test and evaluation performed by the team.

As a result, the author concluded no comparison between 2004 and 2005 results was possible and tabulated results are not presented herein.

In addition, the author concluded no comparison between 2004 and 2005 results was desirable because the number of teams which reported significantly completed test and evaluation in all three categories dramatically increased between the 2004 and 2005 GCE. Prior to the 2004 GCE, most teams had partially completed component test and evaluation only. However, prior to the 2005 GCE, most teams had significantly completed all three categories of test and evaluation.

The author concluded the most significant difference between the 2004 and 2005 GCE was the number of teams which reported test and evaluation of a fully autonomous challenge vehicle, and settled on a simpler objective measure: the number of teams which reported a fully autonomous challenge vehicle capable of waypoint following and path detection, and obstacle detection and avoidance ("fully autonomous challenge vehicle"):

- Prior to the 2004 GCE, no teams reported a fully autonomous challenge vehicle.
- Prior to the 2005 GCE, 21 of 22[35] teams reported a fully autonomous challenge vehicle, including several of the teams which reported incomplete waypoint following and path detection, and incomplete obstacle detection and avoidance test and evaluation. The only team which did not report a fully autonomous vehicle was Team 2005-11. The Team 2005-11 technical proposal was dated August 29, 2005, less than sixty days prior to the 2005 GCE. Team 2005-11 completed 7.2 miles of the 2005 GCE.

The author proposes the difference in the number of fully autonomous challenge vehicles between the 2004 and 2005 GCE may provide an explanation for DARPA's comment that "We are confident that the $2 million prize for Grand Challenge 2005 will be adequate incentive for many teams to do just that." when referring to completing the 2005 GCE. See paragraph XIII.A.

The author selected several teams which reported a focus on test and evaluation. Without exception, these teams had prior experience or focused on the fundamental problem. With one exception, all teams which successfully completed the 2005 GCE had prior experience *and* focused on the fundamental problem, although a focus on test and evaluation was a key factor for several potentially disruptive teams.

- Team 2004-02

Team 2004-02 stated: “The testing strategy establishes reliable control of each component separately before the components are integrated.” ([9], p. 12).

Team 2004-02 described an extensive series of planned tests, but no completed tests, and stated: “At this time, the tests below have not been performed, but will be conducted over the next few months.” ([9], p. 12). The Team 2004-02 technical proposal was dated February 29, 2004, approximately two weeks prior to the 2004 GCE.

- Team 2004-05

Via their response to 2004 SQ 2.b (see Table XXII), Team 2004-05 described extensive planned test and evaluation. Team 2004-05 reported an emphasis on formal methods for software development. See paragraph XIV.D.2.

- Team 2004-10

Team 2004-10 stated: “Extensive testing and evaluation was conducted to evolve vehicle sensing and autonomous steering capability.” ([77], p. 5), and continued with a description of various component and obstacle detection and avoidance test and evaluation.

Overall, Team 2004-10 reported the most comprehensive component and obstacle detection and avoidance test and evaluation of any team which participated in the 2004 GCE. In response to 2004 SQ 2.b, Team 2004-10 stated: “Incremental testing regime will continue as program develops and moves towards higher navigational speeds, more complex real-time processing, and increased sensing capability. Vehicle testing programs will include component, subsystem, speed, and desert local.” ([77], p. 6). Team 2004-10 completed 7.4 miles of the 2004 GCE course, the greatest number of miles completed of any team which participated in the 2004 GCE.

Following the 2004 GCE, DARPA alternately stated: “At mile 7.4, on switchbacks in a mountainous section, vehicle went off course, got caught on a berm and rubber on the front wheels caught fire, which was quickly extinguished. Vehicle was command-disabled.” ([30]) and “At mile 7.4, on the switchbacks in a mountainous section, the vehicle veered off course, got caught on a berm, and could not overcome the obstacle.” ([3], p. 8). However, the actual failure was considerably more complex.

Team 2004-10 was one of few teams which participated in the 2004 GCE to publish its results after the 2004 GCE. Team 2004-10 stated ([39], pp. 36 - 38):

> This failure was a result of a variety of weaknesses acting in concert to end [the challenge vehicle's] race. Entering the corner, the onboard navigation system began to filter out laser data. The filtering

> algorithm was triggered as a result of a sharp angle change in the preplanned path which would not have been present if the path used smooth curves. [A Figure] shows that even though the data was disregarded, the classification of the terrain from the laser scan was still reasonable.
>
> Once the laser data was disregarded, the onboard planning system seamlessly switched to following GPS blindly. At this point, [the challenge vehicle] began to cut towards the inside of the curve. [The challenge vehicle's] GPS measurement of the preplanned path had errors pushing it towards the inside of the curve. In addition, the faceted nature of the preplanned path caused it to be even farther towards the inside of the corner. Finally, the pure-pursuit path tracking software can cause [the challenge vehicle] to cut corners. In this case, these three effects combined to push [the challenge vehicle] roughly 1.5 to 2 meters to the left of the road center such that one wheel fell off of the edge. [A Figure] shows a plot of the pre-planned corridor (inner blue circles), pre-race reconnaissance (green) and [the challenge vehicle's] ground track (black). From this data, the path error seems to be due equally to the above mentioned sources.

The author concluded Team 2004-10 did not perform adequate waypoint following and path detection test and evaluation.

- Team 2005-01

Team 2004-02 participated in the 2005 GCE as Team 2005-01. Team 2005-01's response to 2005 SQ 2.5.1 does not differ significantly from Team 2004-02's response to 2004 SQ 2.a, including repeated errors such as “ODB-II” for OBD-II and “[The challenge vehicle's] GPS system has been tested for accuracy against other COTS GPS system [*sic*].” ([9], p. 12 and [10], p. 13). In addition, Team 2005-01 reported: “The team continues to do cost analysis of the race use of this information.” in reference to OBD-II information and “The LADAR unit has been installed...” ([9], p. 12 and [10], p. 13).

The Team 2005-01 technical proposal is dated August 11, 2005, less than 60 days prior to the 2005 GCE, however Team 2005-01 reported a fully autonomous challenge vehicle: “Extensive testing in the field has led to extensive development of these corner cases.” ([10], p. 11).

- Team 2005-06

Team 2005-06 stated: "[Team 2005-06] has approached the 2005 DARPA Grand Challenge from the standpoint of integrators rather than inventors. This design philosophy has driven its decisions in choosing proven technologies such as the AEVIT vehicle control system and the Oxford integrated INS/GPS, rather than trying to develop these types of technologies itself. This has allowed [Team 2005-06] to focus its considerable manpower on the algorithms and innovative ideas necessary to win the 2005 DARPA Grand Challenge." ([172], p. 2).

Team 2005-06 later stated: "...we would like to think that reaching the finish line after 132 miles of autonomous driving in the desert was not just beginner's luck but rather the result of our simple design methods, good decisions, and good system integration." ([28], p. 525).

The author considers this conclusive evidence that prior experience and extensive corporate or academic sponsorship were not required for a team to successfully complete the 2005 GCE. Team 2005-06 was the only potentially disruptive team to successfully complete the 2005 GCE. As a result, the author considers the Team 2005-06 focus on the 2005 GCE as "integrators" to be a distinguishing key factor.

- Team 2005-09

Team 2005-09 stated: "Specific testing and regression testing was performed nearly daily for short focused evaluations." ([175], p. 6); "[The challenge vehicle] development has been driven by two overarching themes. The first is to do small increments of a develop, simulate, test, and regression cycle. The second is to continuously develop an end-to-end system built with agents of comparable complexity and quality. This approach means at any time the vehicle has all the necessary components to operate and shifts the emphasis from novel ideas to the interaction and integration of agents." ([175], p. 6); and "The end to end testing of [the challenge vehicle] was performed in stages. Early on we had many short specific tests on a nearly daily basis. Specific tests included a series of vibration and sensor fouling experiments. As the site visit approached we became focused on meeting the specific challenges of the site visit and focused specifically on the waypoint following and trash cans as obstacles. In July we went to the Mojave Desert to test the fully integrated vehicle. We tested for distance, responsiveness to the environment, effects of terrain and overall reliability. This was sufficient to convince us we could compete in the DGC. The final testing phase is emulating the NQE environment and identified NQE evaluation components." ([175], p. 9).

Team 2005-09 stated: "[Team 2005-09] is sponsored by the MITRE Corporation. MITRE is a collection of Federally Funded Research and Development Centers that support the DoD, FAA, IRS and other federal agencies." ([175], p. 2). The author proposes Team 2005-09's focus on test and evaluation may have been a result of the team's primary group identity and background in system integration.

Team 2005-09 completed 0.7 miles of the 2005 GCE course, the least number of miles of any team which participated in the 2005 GCE. Team 2005-09 stated the challenge vehicle detected occasional dust clouds as transient obstacles, which ultimately caused the challenge vehicle to veer off course where it was unable to continue because "the lasers could not differentiate between weeds and large rocks" ([52], p. 835). See paragraph XIII.B.5.

However, Team 2005-09 also stated: "A major challenge of the system has been the self imposed requirement that the system be reusable and adaptable to the needs of a variety of our sponsors." ([175], p. 3) and "Given our incredibly short time to prepare, a key challenge for us was to sustain a rapid pace of incremental development while maintaining system coherence. In order to ensure what we learn is of high utility to our sponsors we also had a self imposed challenge of reusability and extensibility of design and code." ([175], p. 9).

As a result, although Team 2005-09 attributed the cause of their failure to complete the 2005 GCE to errors in obstacle detection, the author concluded the ultimate cause may have been a lack of available resources, specifically time in which to perform adequate test and evaluation of the team challenge vehicle.

- Teams 2005-13 and 2005-14

Teams 2005-13 stated: "A vigorous testing program has demonstrated reliable, high-speed navigation including a 7-hour 200-mile endurance run, reliable obstacle avoidance at 35 mph and peak speed of 54 mph." ([11], p. 2), "[Team 2005-13] has been testing [the challenge vehicle's] systems and subsystems since it became operational in December of 2003. [The challenge vehicle] has accumulated over 3000 autonomous test miles." ([11], p. 15), and "In addition to these system tests, [The challenge vehicle] has tested for software endurance via simulation, dust detection, pointing, shock and vibration." ([11], p. 15).

Team 2005-14 stated: "A vigorous testing program has demonstrated reliable, high-speed navigation including a 7-hour 200-mile endurance run, reliable obstacle avoidance at 35 mph and peak speed of 40 mph." ([12], p. 2), "[Team 2005-13] [*sic*] has been testing [Team 2005-14 challenge vehicle's] systems and subsystems since it became operational in December of 2003. [The Team 2005-14 challenge vehicle] has accumulated over 500 autonomous test miles." ([12], p. 15), and "In addition to these system tests, [the Team 2005-14 challenge vehicle] has tested for software endurance via simulation, dust detection, pointing, shock and vibration." ([12], p. 15).

Although Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE, Team 2005-14 did not participate in the 2004 GCE. See paragraph XIV.D.1.

- Team 2005-16

Team 2005-16 stated: “A major emphasis of [Team 2005-16] has been early development of a prototype end-to-end system, to enable extensive testing in authentic desert terrain.” ([195], p. 1), “From the beginning of this project, [Team 2005-16] has placed a strong emphasis on in-field development and testing. Initial tests of a preliminary end-to-end system took place in December 2004. Since this time, [the challenge vehicle] has logged many hundreds of autonomous miles.” ([195], p. 2), and “Testing has played a major role in the development of [the challenge vehicle].” ([195], p. 12). Team 2005-16 described a comprehensive test and evaluation program culminating in endurance testing of a fully autonomous vehicle.

- Team 2005-18

Team 2005-18 stated: “[Team 2005-18] makes use of a spiral development process to guide our efforts as we make progress toward the completion of the DARPA Grand Challenge. Spirals are defined phases in the projects development moving outward from the initial point. Each spiral outward adds a new layer of functionality that future layers can build upon. A given spiral passes through the following phases: define, design, build and test. A spiral process is far more useful for a project like ours that requires multiple components that all depend on one another to be developed in parallel since any given component can always depend on the level of functionality of the other components in the previous spiral.” ([197], pp. 12 - 13).

Team 2005-18 also stated: “Development and testing of individual modules and full system integration is achieved through an extensive test plan.” ([197], p. 13).

- Team 2005-20

Team 2005-20 stated: “[The challenge vehicle] has been thoroughly tested in many different environments. A mockup of last years QID was constructed on a farm (site visit location) to test path following, high speed navigation, and obstacle avoidance. During the development of this system we have endured many failures. Countless hours have been used investigating computer failures/corruptions, network failures, electrical issues, and a few mechanical failures. This experience has led to redesign of some components of the vehicle, improved cooling for computers, and knowledge of critical spare parts to have on hand.” ([56], p. 14).

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: “[The Team 2005-22 challenge vehicle] was subjected to extensive simulated and live testing in preparation for the 2005 Grand Challenge.” ([58], p. 12) and “[The Team 2005-23 challenge vehicle] underwent extensive simulated and live testing in preparation for the 2005 Grand Challenge.” ([164], p. 6). Both teams reported extensive test and evaluation, including the use of a “vehicle simulator program" to "test conditions and situations that would be difficult, if not impossible, for [the challenge vehicle] to encounter in Blacksburg" ([58], pp. 12 - 13 and [164], p. 6) and which "allowed for testing during conditions where it would normally not be possible, such as at night or during heavy rain" ([58], p. 13 and [164], p. 6). See paragraph XIV.D.1.

XIV.D.2. Use robust software development methodologies

Several teams reported robust software development methodologies were in use by the team. For example:

- Team 2004-04

Team 2004-04 stated: "The Smart Sensor Arbiter component provides a central point for fusing all smart sensor data. The Smart Sensor architecture was defined in such a way that all sensors and the arbiter use the same message interface. The benefits of doing this are two-fold. First it allows the option of having the Smart Sensors share code for the core Smart Sensor functionality. This reduces development time by allowing the core code to be rigorously tested and debugged while each sensor developer works on their sensor data processing." and "The Smart Sensors can also be used individually as input to the Smart Sensor Arbiter allowing the sensors to be tested and debugged with the Reactive Planner component individually." ([44], p. 7).

- Team 2004-05

Team 2004-05 stated: "The software is developed according to well defined formal methods based on the SEI-CMM; with design documents, coding standards, and state and timing charts." ([45], p. 3). Team 2004-05 also stated: "The application and driver software will be verified using formal methods based on UML for Real Time, as well as other methods such as Rate Monotonic Analysis and Dynamic Monotonic Analysis as appropriate. Each software module will have a formal test plan and software test harness that can be executed on the development machines, and there will also be formal integration and performance tests." ([45], p. 7).

- Team 2005-06

Team 2005-06 stated: "Early on in the planning process for the Grand Challenge, [Team 2005-06's] development team decided that they would use the Java programming language to develop as much of the software as possible. This decision was made due to Java's proven track record of stability, rapid development, simple threading capabilities, and portability. Using Java allowed the development team to concentrate on the real issues, rather than having to spend considerable time debugging memory leaks and complex threading issues." ([172], p. 7).

Team 2005-06 also stated: "In order to reduce errors, [Team 2005-06] has chosen to integrate the powerful unit testing framework JUnit throughout its entire development process. By using JUnit, [Team 2005-06] can write tests for independent modules of its code base and then automatically run these tests whenever new code is deployed to the autonomous vehicle. This ensures that as development progresses no bugs are introduced into pieces of code that were previously working." ([172], p. 8).

- Team 2005-17

Team 2005-17 stated: "Daily builds of the software are tested against a collection of test cases gathered from the real world. Developers perform unit level testing of changes to the software using the combination of the vehicle simulator and visualization tools included in the software suite." ([140], p. 10).

- Team 2005-18

Team 2005-18 stated: "[Team 2005-18] uses proven open-source tools as a critical part of our code-development. All code is written in C/C++. The source tree is managed with the subversion source control system, allowing for versioning control. Additionally, HTML documentation of the source tree is automatically generated by doxygen. The bugzilla tool from the Mozilla project is used to track the different bugs we inevitably encounter in the team source tree. Bugzilla is also used to manage tasks assigned to different members of the team. The team also maintains a wiki for general documentation. This [*sic*] extent of this documentation ranges from meeting minutes to sub-system documentation and status. The HTML format of the wiki makes our documentation easily accessible to the members. Finally, the team also maintains a web based discussion board for its members to further discuss any new ideas or large issues that come up when its hard to get everyone together for a meeting." ([197], p. 13).

- Team 2005-20

Team 2005-20 stated ([56], p. 8):

> A variation of Extreme Programming was utilized to develop the majority of the software. A rough architecture was initially sketched out, but the details of the various implementations were left somewhat vague. A core set of classes were developed and ported to all operating systems. Hardware and software architectures were enumerated, as many of the sensors have very specific hardware requirements. A communications layer was developed, and then the individual applications were developed in parallel with simulators and other proprietary testing tools. Code reviews were performed, and large discussions

were held before refactoring certain experimental algorithms. A very large emphasis was placed on using well-known design patterns and STL libraries.

A primary development process for the software was to develop a simulator using the actual real-time PXI controller software. Since the real-time modules are the same ones that run the robot, any conflicts or errors would be immediately evident in the simulation. The simulator estimates where the vehicle position would be based on the commands sent instead of reading its position from a GPS device, but is otherwise identical to the software on the robot. This facilitates testing and optimization of the complex interaction between the path planner and PXI without the need to operate the vehicle.

- Team 2005-21

Team 2005-21 stated ([160], p. 13):

The software was developed and testing in phases utilizing different test methods. These test methods included software peer reviews, simulations on host, lab testing, and testing on the vehicle.

Software peer reviews were held for code that was considered either complex in nature, or a critical interface between two functions. At each software review, members of the team were invited to review the code. Action and questions were formally documented for later investigation and resolution by the coder.

- Teams 2005-22 and 2005-23

Team 2005-22 stated: "The software on [the challenge vehicle] was created using National Instruments' Labview 7.1. This program allows team members with knowledge of control systems but little programming experience to program the vehicles [*sic*] behavior. Certain parts of the programs are written in C; however, these pieces are converted into files that are later used by the larger Labview code. Another large benefit of using Labview is the ease of creating vehicle interfaces within the programs. Any team member can easily create an interface that monitors all vehicle action during autonomous operation. This allows for quick and easy debugging to [*sic*] any problems that appear during testing." ([58], p. 3).

Team 2005-23 stated: "The software on [the challenge vehicle] was created using National Instruments' Labview 7.1. This programming language allows team members with knowledge of control systems but little programming experience to program the vehicles [*sic*] behavior. Certain parts of the programs are written in C; however, these pieces are converted into .dll files that are used by the larger Labview code. Another large benefit of using Labview is the ease of creating vehicle interfaces within the programs. Any team member can easily create an interface that monitors all vehicle action and sensor data during autonomous operation. This allows for quick and easy debugging to [*sic*] any problems that appear during testing." ([164], p. 3).

XIV.D.3. Simulate sensor noise and sensor failure

DARPA cautioned teams might encounter sensor noise or sensor failure. DARPA stated: "Prospective Entrants also are advised that there could be dust, smoke, or other visual obscurants on the Route, and that visual spectrum only sensing may not permit sufficient speed if those situations are encountered (such as when following another vehicle)." ([1] and [6]).

DARPA also cautioned teams should not rely solely on GPS, and that GPS reception was not guaranteed. DARPA stated: "GPS alone will not provide adequate navigation information to a Challenge Vehicle." and "GPS reception at Waypoints is not guaranteed." ([1] and [6]).

Several teams described strategies to simulate or otherwise reproduce sensor noise or sensor failure or reported test and evaluation to determine the effects of sensor noise or sensor failure. For example:

XIV.D.3.a. Noise

- Team 2005-04

Team 2005-04 stated: "Compensation for vibration and other vertical motion is done in software, using the IMU data, specifically generating a 'ground plane' that can be referred to, while doing sensor fusion." ([169], pp. 9 - 10).

- Team 2005-05

Team 2005-05 stated: "We have tested the vehicle in moderate rain. Although the rain did introduce noise into the ladar measurements, our obstacle detection software appeared fairly robust to this noise." ([34], p. 13).

- Team 2005-09

Team 2005-09 stated: "Early on we had many short specific tests on a nearly daily basis. Specific tests included a series of vibration and sensor fouling experiments." ([175], p. 9).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: "...[the challenge vehicle] has tested for software endurance via simulation, dust detection, pointing, shock and vibration." ([11], p. 15 and [12], p. 15).

XIV.D.3.b. GPS "jump" and position error

GPS "jump" or "drift" was consistently reported by teams which participated in the 2004 QID or GCE or 2005 GCE. For example, Team 2005-05 stated: "Very often, especially when the vehicle would drive near a wall or approach a tunnel, there would be highly erratic jumps in the GPS measurements due to multipath reflections." ([170], p. 542).

In addition, GPS sensor failure was directly implicated in the failure of five teams to complete the 2005 GCE: Teams 2005-02, 2005-09, 2005-15, 2005-18, and 2005-19.

DARPA, via 2004 SQ 1.g.2 (see Table XXII) and 2005 SQ 2.2.1 (see Table XXIII) requested teams describe how they would handle "GPS outages". In general, teams described how the challenge vehicle controlling intelligence would continue to determine position reliably in the absence of GPS data. A few teams described test and evaluation to determine the effect of GPS outage on the challenge vehicle controlling intelligence. For example:

- Team 2004-05

Team 2004-05 stated: "In the event of a total loss of GPS signals, the system can maintain an accurate location estimate by 'dead reckoning', using the four independent wheel rotation encoders in conjunction with two independent heading determination subsystems, a gyro and an electronic compass sensor." ([45], p. 6).

- Team 2004-07

Team 2004-07 stated: "In the absence of GPS, the vehicle will attempt to proceed by dead reckoning using IMU and odometry data. If the vehicle is on a known trail and following the trail is consistent with remaining on the Challenge Route, the vehicle will follow the trail and use odometry data to infer the distance traveled along it. As the uncertainty of its position grows larger, the vehicle may replan its route to avoid the Challenge Route boundaries, i.e., other things being equal it may try to remain in (what it thinks is) the center of the Challenge Route corridor, even if this is not the shortest route." ([46], p. 8).

- Team 2004-08

Team 2004-08 stated: "In the case of lost GPS signal, we will still receive data from our POS LV regarding current location and other related information. The GPS will automatically update the location in the device when signal is available. As outlined in the table below, without GPS input for a two-minute time span this unit will stil [*sic*] be accurate within 0.60 meters." ([76], p. 6). Team 2004-08 also stated: "...if our vehicle leaves GPS coverage, it will just run off of the INS. When the system loses GPS input for a two-minute time span this unit will stil [*sic*] be accurate within 0.60 meters." ([76], pp. 4 - 5).

- Team 2004-13

Team 2004-13 stated: "In case of short temporary loss of GPS signal, the IMU is able to determine the location of the vehicle, although with an increasing error." ([232], p. 5).

- Team 2004-14

Team 2004-14 stated: "In the absence of GPS data due to communication outages the IND/DGPS [*sic*] system is aided by a 3D-magnetometer and the vehicle's odometer. The Kalman filter of the Navigation system continuously blends the INS/DGPS data with the odometer and magnetic compass. As a result the compass and odometer are constantly calibrated and provide fairly accurate information. During GPS outages the INS uses only odometer and magnetic compass data to aid the inertial data." ([132], p. 6).

- Team 2004-17

Team 2004-17 stated: "We have tested the ability of various materials to block antenna reception. Flat sheets of aluminum and Lucite were unable to block the GPS, as multi-path reflections off of the ground still reached the antenna. Wrapping the antenna in aluminum foil cut off reception (we can selectively cut off satellites and simulate GPS outages)." ([142], p. 12).

- Team 2004-20

Team 2004-20 stated: "We are currently planning to use a Novatel ProPack LBHP GPS with Omnistar corrections, along with a Crossbow AHRS inertial system. This combination should give us location to within 20cm with GPS information available, and in dead-reckoning mode, we expect to have drift rates of perhaps 1 degree per minute in heading." and "The INS system and magnetic compass will take over, but drift is to be expected. If GPS is lost while on a well-defined road, or in an area where there is no alternative path, the road-following and collision-avoidance systems should be sufficient to keep the vehicle on course. Long GPS outages will result in increasing uncertainty as to position and, if this occurs in an area where the course boundaries are narrow, this may result in problems. For safety reasons, speed will be reduced during GPS outages." ([107], p. 7).

- Team 2005-05

Team 2005-05 stated: "The NovAtel Propak-LBPlus GPS has a nominal position accuracy of 20 cm, but under adverse conditions, this accuracy figure can become meaningless. For example, when passing into the shadow of a metal structure, we have witnessed sudden changes in reported position of over 100 meters. We use a Kalman filter which includes the steering properties of the truck in its physical model of the system to reject transient errors of this type. Under typical route conditions we estimate we can maintain a position accuracy of under 30 cm." ([34], p. 5).

- Team 2005-06

Team 2005-06 stated: "Another extremely effective test involved manually steering the vehicle off course at high speed and then switching back to autonomous mode. This simulated a GPS jump, which can occur rather frequently. After noticing that the navigation system abruptly turned the steering wheel to counteract this jump, the navigation system was updated to eliminate this abrupt movement." ([172], p. 12).

- Team 2005-10

Team 2005-10 stated: "A MIL-NAV inertial navigation system from Kearfott is computing position at 50 Hz and becomes the primary source of position information when the Navcom reports its data as invalid. It also serves as an error check for the Navcom data." ([176], p. 3).

- Team 2005-21

Team 2005-21 stated: "During most of the integration and development testing, the antennas for the RT3100s were mounted on the roof of the cab on an aluminum sheet ground plane. For the actual race, the cab was reduced in height and the antennas were mounted on the roll bar just behind the cab. The small patch antennas that were initially used with the RT3100s, were replaced later in the testing phase with GPS-701 antennas from Novatel. It was discovered that the small patch antennas seemed particularly susceptible to interference. In order to obtain a more accurate position solution and eliminate any errors over time, the position solutions from the two RT3100s were averaged together. In the case of a failure of one of the RT3100s, the system will switch to using the remaining RT3100 as the sole GPS source." ([160], p. 9)

XIV.D.3.c. Other sensor failure

- Team 2005-11

Team 2005-11 stated: "Scenarios were developed to mimic the loss of data as well as terrain obstacles. Multiple simulation runs, particularly obstacle avoidance scenarios, were executed prior to field testing. Both the hardware and software were modified to attempt to remedy shortcomings identified during testing." ([182], p. 9).

• Team 2005-12

Team 2005-12 stated: “Stereovision has clear advantages over LIDAR in rain as light rain will not affect image quality unless it collects directly on the lens. In addition, water or other obstructions on the lenses produce holes in the depth image that will preclude detection in these areas but will not generate false positives.” ([185], pp. 5 - 6).

XIV.D.4. Develop tools to analyze the results of test and evaluation

Several teams reported the development of tools to analyze the results of test and evaluation. For example:

• Team 2005-05

Team 2005-05 stated: “We devoted considerable effort to our visualization/control interface software, called 'Dashboard.' All sensor data is logged while the vehicle is running and can be examined by Dashboard in real time or replayed later. Some interesting features of Dashboard are: 3D visualization in space of the truck’s location, heading, and wheel angle, the location of waypoints, ladar reflections, video imagery, inferred obstacles and trail boundaries, the planned route, and current and future planned speed; also the ability to pan, rotate, and zoom to different viewpoints; the ability to measure distances and angles between any points on the screen; and very importantly, the ability to scroll backwards and forwards in time when replaying a 'movie' from logged data. In this way we can find the critical moments of a test run and visualize exactly what the state of the vehicle was at that time, what it sensed, and what decisions it made. This is very useful in debugging.” ([34], pp. 4 - 5).

• Team 2005-18

Team 2005-18 stated: “An important feature of all modules is their ability to log raw data and reply [*sic*] the data for offline debugging and testing. This capability is used frequently in testing and allows a detailed analysis of failures and the ability to replay data through the system to verify that modifications solve the intended problem.” ([197], p. 13).

• Team 2005-20

Team 2005-20 stated: “In addition, a software program called HANSEL was developed for viewing the GPS data on satellite image maps. This program has evolved into a very significant part of the system diagnostics program. All the time stamped obstacle data, planned path data, and actual traveled path are plotted on the map. This map shows when the vehicle saw the obstacle, when the new path was sent to the controller, and the final result of the vehicle motion all represented in global position and time. Each obstacle is color coded to indicate which sensor saw which obstacle and where it was located relative to the vehicle.” ([56], p. 8).

- Team 2005-21

Team 2005-21 stated: “Rockwell also developed a simulation environment that included all of the vehicle dynamics. This simulation was used to test the vehicle control interface, real-time path planner and behavior control. Similar to on the vehicle, a series of waypoint could be executed while avoiding planned obstacles. The 2004 race path was executed several times in this simulation environment to determine if the vehicle could navigate the entire path.” ([160], p. 13).

- Team 2005-22

Team 2005-22 stated: “A second set of software allowed various data recorded from the vehicle to be replayed for analysis. This replay software played back information such as vehicle position and orientation, speed, throttle and brake percentages, and LIDAR scans at the same speed that it was originally recorded. Being able to play back exactly what happened during autonomous runs is valuable to determine exactly how [the challenge vehicle] behaved in the real world.” ([58], p. 13).

- Team 2005-23

Team 2005-23 stated: “A second set of testsoftware [*sic*] allowed various data recorded from the vehicle to be replayed for analysis. This replay software played back information such as vehicle position and orientation, speed, throttle and brake percentages, and LIDAR scans at the same speed that it was originally recorded. Being able to play back exactly what happened during autonomous runs was valuable to see exactly how [the challenge vehicle] behaves in the real world.” ([164], p. 6).