1. The text of the footnote reported by DARPA differs slightly from the text of the Fiscal Year 2001 National Defense Authorization Act, which stated: “It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that... by 2015, one-third of the operational ground combat vehicles are unmanned.” ([4], p. 46).

2. Teams are referred to by the unique combination of year and identifier throughout this technical report. For example, Axion Racing is referred to as “Team 2004-02” for the 2004 QID and GCE, and “Team 2005-01” for the 2005 GCE. See Table III for a list of team reference numbers.

3. Many teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team. See Chapter XI. Several teams reported pre-mapping prior to the race effectively eliminated from consideration for the controlling intelligence all terrain but the actual course defined by the RDDF. The task of the controlling intelligence was therefore made simpler, and became one of distinguishing the course from terrain which had been eliminated from consideration by the team, and avoiding unintended obstacles.

   Statements similar to those made by Teams 2004-01 and 2004-02 were typical:

   - Team 2004-01 stated: “Terrain outside of Challenge route boundaries is written to the local map as completely impassable. The AI will not consider traversing these areas under any circumstances” ([8], p. 5).

   - Team 2004-02 stated: “At the beginning of the DARPA Grand Challenge race, the participants are provided with GPS waypoints and error margin information. [The challenge vehicle] recognizes these boundaries in its mapping engine, and makes all decisions based upon the knowledge that it should not pass these boundaries.” ([9], p. 10).

4. Several teams referred to the key components or technologies in use by the team as well-known. Statements similar to those made by Teams 2004-02, 2005-01, 2005-13, and 2005-14 were typical:

   - Team 2004-02 stated: “An autonomous vehicle race through the desert such as the DARPA Grand Challenge presents tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The challenges can be broken down into the following distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology.” ([9], p. 2).

Team 2004-02 participated in the 2005 GCE as Team 2005-01. Team 2005-01 stated: "The DARPA Grand Challenge provides tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The Challenge can be broken down into distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology." ([10], p. 2).

- When describing their general approach to the Grand Challenge, Teams 2005-13 and 2005-14 stated: "These distinctive technologies, combined with solid implementation of well-known basics like pose estimation, waypoint following and path tracking drive [the challenge vehicle]." ([11], p. 2 and [12], p. 2).

In addition, the author considers the following observations support this conclusion:

- References describing or documenting key components or technologies in use by teams participating in the 2004 QID or GCE or 2005 GCE generally pre-date the Grand Challenge by several years, as a minimum, indicating they were known at the time of the Grand Challenge. Several teams cite these references in their technical papers and results published via the Journal of Field Robotics.

- Teams participating in the 2004 QID or GCE or 2005 GCE made extensive use of COTS components, with successful teams and most potentially disruptive teams being integrators of existing COTS components. In general, teams which attempted to re-implement existing technologies were not successful. This will be discussed in detail throughout this technical report.

5. It is unclear what DARPA intended by the phrase "average minimum speed". The phrase is interpreted herein as "average speed".

6. DARPA stated: "No vehicle was able to complete the 142-mile Grand Challenge route." ([3], p. 7).

7. DARPA stated: "The Defense Advanced Research Projects Agency (DARPA) today announced that five autonomous ground vehicles successfully completed the DARPA Grand Challenge..." ([5]). The use of "success" to mean "completed the Grand Challenge", does not conform to criteria published by DARPA prior to the event, and is not used herein.

8. The author's lack of familiarity with PHP at the beginning of this research, specifically, the use of “$” for identifiers, including variable names, resulted in manual calculation to determine the cause of a 0.1 - 12.5% variance in distance calculated using Vincenty's Inverse Formula.

   While attempting to determine the cause of the variance, several errors in current PHP and Javascript references were identified which made diagnosis difficult:

   - Descriptions provided for PHP functions `sin()` ([14], p. 441), `tan()` ([14], p. 451), `asin()` ([14], p. 383), and `atan()` ([14], p. 384) were identical. The description provided for `sin()` was reported as “corrected” by the publisher as of the April, 2006 printing; the description provided for `tan()` was reported as “unconfirmed”.

   - A reference incorrectly gives the concatenation assignment operator “`.`=” as “`.`+” ([14], p. 478). This had not been reported by the publisher as a known error as of the April, 2006 printing, and was reported to the publisher by the author.

   - A reference stated: “...M specifies the number of digits before the decimal point, while D gives the number of places after the decimal point.” ([15], p. 147). However, both versions “5.0” and “6.0” of the MySQL Reference Manual state: “'(M,D)' means that values can be stored with up to M digits in total, of which D digits may be after the decimal point.” ([16]). Therefore, M gives the number of digits total, including those before and after the decimal point. Review of the third edition of this reference indicated this error is still present on page 144. Based on the author's personal experience, the author proposes this may be a translation error.

9. DARPA stated that latitudes and longitudes are given as type FLOAT ([13], p. 1). However, when attempting to read latitude and longitude values from the 2004 QID, 2004 GCE, and 2005 GCE RDDF into a MySQL database using the RDDF analysis application, specifying FLOAT in lieu of DOUBLE caused errors in the values of the latitudes and longitudes in the 5th, 6th, and 7th position after the decimal place.

10. DARPA made resources and references available to teams participating in the 2004 QID or GCE or 2005 GCE via the Grand Challenge website, such as several revisions of the 2004 GCE rules, a “description of the mandatory subjects to be addressed” in the team technical proposal, and the 2004 QID and GCE RDDF. The Grand Challenge website was substantially redesigned prior to the 2005 GCE. DARPA re-published portions of the Grand Challenge website as the Archived Grand Challenge 2004 website ([17]), but did not retain all published records. As a result, the Archived Grand Challenge 2004 website is an incomplete record of events.

11. Analysis of the 2004 GCE RDDF revealed that the Maximum Crossing Time does not correspond to the "time by which a Challenge Vehicle must pass that Phase Line Waypoint in order to remain in the Challenge." ([1]). The Maximum Crossing Time for waypoint 2024 ("16:30:00") was ten hours after the first vehicle departed the starting chute on the day of the race: "At 6:30 AM on Saturday, March 13, 2004, [the Team 2004-10 challenge vehicle] sped from the starting chute at the Slash X Ranch in Barstow, California, marking the start of the DARPA Grand Challenge" ([3], p. 7).

The other challenge vehicles participating in the 2004 GCE began the course over the next two hours ([3], p. 7). Vehicles not having completed the course by the Maximum Crossing Time for waypoint 2024, the final Phase Line Waypoint, or any waypoint between waypoint 2024 and waypoint 2585, the final waypoint, could not have successfully completed the course in ten hours (see Table IV). As a result, the author was unable to determine what DARPA intended by specifying Phase Line Waypoints with a Maximum Crossing Time.

12. Vincenty stated ([21]):

```
Distances obtained from the inverse solution and
rounded off to the millimeter may be in error by up to
0.5 mm, which represents 0.000015″ in the direction of
the line.
```

13. According to paragraph 2 ("Notation") of Vincenty, *f* is a function of *a* and *b* ([21]). However, *a* and 1/*f* are considered "Defining Parameters" with "adopted values" by the National Imagery and Mapping Agency (NIMA), and the value of *b* is a "Derived Geometric Constant" ([22]). As a result, the RDDF analysis application does not calculate *f* in accordance with Vincenty ([21]), but uses the values for *a*, *b*, and *f* reported by NIMA ([22]).

14. NIMA stated ([22]):

```
In common practice the geoid is expressed at a given
point in terms of the distance above (+N) or below
(-N) the ellipsoid.  For practical reasons, the geoid
has been used to serve as a vertical reference surface
for mean sea level (MSL) heights.  In areas where
elevation data are not available from conventional
leveling, an approximation of mean sea level heights,
using orthometric heights, can be obtained from the
following equation:

H = h - N

where:
```

h = geodetic height (height relative to the ellipsoid)

N = geoid undulation

H = orthometric height (height relative to the geoid)

15. DARPA reported at least two different 2005 GCE course lengths. DARPA stated: "At least three robots successfully completed a grueling 131.2-mile course in the Mojave Desert today..." ([26]).

The next day, DARPA stated: "...five autonomous ground vehicles successfully completed the DARPA Grand Challenge, a tough, 131.6-mile course in the Mojave Desert." ([27]).

The latter length, from a source published after the 2005 GCE, is used herein.

This was a relatively common error. Course length and average course segment length were variously and incorrectly reported by both DARPA and some teams which participated in the 2004 and 2005 GCE. For example, Team 2005-06 stated: "[The course] consisted of a series of GPS waypoints which were an average of 275 feet apart." ([28], p. 510). The 2005 GCE RDDF defines 2934 course segments. See paragraph II.C.2. An average course segment length of 275 ft would have resulted in a course length of 152.8 miles (245.9 km), approximately 21.2 miles greater than the 2005 GCE course.

16. The author notes the course length calculated for the "smoothed" 2005 GCE course conforms more closely to the 131.2-mile course length reported by DARPA ([26]). The error in calculated course length was less than 0.1 percent.

17. While evaluating data resulting from the 2004 and 2005 RDDF analysis, the author noted, and initially attached significance to, the fact that some of the speeds in the 2004 and 2005 RDDF naturally result in turns of diameters which match the squares of the numbers from one to 12.

This can be explained by the fact that one mile per hour equals 0.1998 meters per second, and is essentially equivalent to one-fifth (1/5) m/s. As a result, there is a natural confluence with speeds that are multiples of five mph defined by the RDDF.

Compounding this observation, for the SSF chosen as the reasonable lower bound in the analysis above (1.02):

$$\frac{1}{(g \cdot SSF)}$$

is equal to:

$$\frac{1}{(9.80 \cdot 1.02)}$$

which is essentially equivalent to one-tenth (1/10) m/s^2.

Therefore, calculated radii are essentially equivalent to the square of the speed, divided by five, which is in every case a multiple of five, which is then divided by ten. See Table VIII.

The author concluded this is a consequence of the selected geometry, and converting between miles per hour and meters per second using known values, i.e., the number of feet in one mile (5280), number of seconds in one hour (3600), and number of feet in one meter (3.2808399), which had no other significance but may otherwise be convenient for course designers.

18. Although commercially-available ATVs were also popular, their potential as military service vehicles is limited by reduced cargo capacity. No vehicle based on a commercially-available ATV completed the 2005 GCE course.

19. This section was amended in 2006 by Public Law 109-364, Section 212(a)(1), which substituted “Director of Defense Research and Engineering and the service acquisition executive for each military department” for “Director of the Defense Advanced Research Projects Agency” and “programs” for “a program” ([60]).

20. The FCS was canceled June 23, 2009 ([62]). Two of three planned MULE variants were cancelled following a U. S. Army review of the Army's short- and long-term modernization requirements in December, 2009: the XM1217 MULE-T and XM1218 MULE-CM ([63]).

21. Various NovAtel sensors reported to be in use by the teams included: “Anovatel Pro-Pack LB” (Team 2004-18), “Novatel ProPack LBHP GPS” (Team 2004-20), “Novatel ProPac-LB-HB” (Team 2004-22), “Novatel Propack -LB” (Team 2004-23), “Novatel ProPak-LB” (Team 2005-03), “Novatel Propak LB-L1L2” (Team 2005-04), “NovAtel Propak-LBPLus” or “Novatel ProPak LB-Plus” (Team 2005-05), “NovAtel ProPAK-LBplus” (Team 2005-08), “Novatel Pro-Pack LB dual frequency (L1/L2)” (Team 2005-20), and “Novatel Propak LBplus” (Teams 2005-22 and 2005-23).

    Neither the manufacturer website ([149]) nor “Discontinued Products List” ([150]) reported a “NovAtel ProPak-LB” product exists. However, the “Discontinued Products List” referred to a family of “NovAtel ProPak-LBplus” products with specific model numbers such as “PROPAK-LB+HP” and “PROPAK-LB+HP-L1L2”.

Unless otherwise noted, the author considers it likely a NovAtel ProPak-LBplus DGPS receiver was in use by the teams.

22. Via a "NOTE" in revision "5 January 2004" of the 2004 GCE rules, DARPA stated: "GPS data for the RDDF was collected using a NAVCOM StarFire™ GPS system..." ([6]), which may explain the popularity of NavCom DGPS receivers.

Six teams which participated in the 2004 QID and GCE reported one or more NavCom DGPS receivers were in use by the team: Teams 2004-04, 2004-06, 2004-13, 2004-14, 2004-17, and 2004-24. See Table XXVI.

Six teams which participated in the 2005 GCE reported one or more NavCom DGPS receivers were in use by the team: Teams 2005-01, 2005-02, 2005-03, 2005-10, 2005-15, and 2005-18. See Table XXVIII.

All teams which reported a NavCom DGPS sensor were in use by the team were selected to participate in either the 2004 or 2005 GCE.

23. Teams 2004-05 and 2004-12 reported LIDAR sensors with capabilities similar to the SICK LMS 291 product family were in use by the team. However, neither team was selected to participate in the 2004 GCE. Eighteen unknown SICK LIDAR sensors were in use by teams which participated in the 2004 GCE, some of which may have been LIDAR sensors with capabilities similar to the SICK LMS 291 product family. See Table XLIII.

24. Both the SICK LMS 211-30206 and 221-30206 include an internal heater as a feature, allowing them to operate in temperatures to -30ºC ([75]). An internal heater is available for the SICK LMS 291 product family as an accessory. SICK does not publicly disclose pricing information. See paragraph V.E.2.d.i. However, the author considers it reasonable to conclude the price of a sensor with an internal heater exceeds the price of the same sensor without the internal heater.

25. Teams 2005-04 and 2005-21 participated in the 2004 GCE as Team 2004-23. Team 2005-04 stated: "As [Team 2005-04] were the team that developed the sensing and intelligence for [Team 2004-23], a number of aspects of [the Team 2005-04 challenge vehicle] are descendants of technology and approaches we used in 2004 and a number of individuals participated in this endeavor through its development." ([169], p. 2).

26. The Team 2005-07 technical proposal was unavailable for review. See paragraph V.C.32. In addition, the Team 2005-11 technical proposal table of contents referred to a paragraph 2.2.2 ("Utilization of Mapping Data"), but the technical proposal contains no paragraph numbered "2.2.2" or titled "Utilization of Mapping Data".

27. This definition of the fundamental problem of the Grand Challenge is at odds with various team definitions, including that of the team which placed first during the 2005 GCE: Team 2005-16. Team 2005-16 stated: “The strong emphasis on software and vehicle intelligence indicates [Team 2005-16's] belief that the DARPA Grand Challenge is largely a software competition.” ([195], p. 2).

28. Alternately, the proposed 2005 GCE course length may have been the average of the “average minimum speed of approximately 15 - 20 mph” multiplied by a maximum corrected time of ten hours. However, a challenge vehicle completing the 2005 GCE course with a proposed length of 175 miles in ten hours would have been required to exceed a minimum speed of 15 mph to successfully complete the 2005 GCE.

29. Based on the author's personal experience, Teams 2004-10 and 2005-13 may have been able to eliminate the use of a generator and batteries by selecting the M1097A2 “heavy variant” HMMWV as challenge vehicle platform in lieu of the M998 due to its heavy duty 200 A alternator ([245]).

30. Team 2005-06 stated ([172], pp. 5 - 6):

All of [Team 2005-06's] LADAR sensors require 24 volts. Rather than provide this power from the hybrid’s 12 volt electrical system, [Team 2005-06] chose to instead provide a separate 24 volt electrical system for these sensors. This electrical system consists of two large-capacity 12 volt batteries connected together to provide 24 volts of power. These batteries alone will provide over ten hours of power. This would provide enough power for the race alone, but not if the vehicle was paused for an extended period of time...

To ensure that the batteries will always be near full capacity, [Team 2005-06] installed six solar panels on top of the vehicle. These solar panels are high efficiency, and will consistently provide over 150 watts of power even in low-light conditions. Since the Grand Challenge will be run in the desert during the day, a sufficient light source is expected to be available at all times.

31. Several teams also referred to modifications to the challenge vehicle's suspension to increase ground clearance or otherwise make the challenge vehicle more suitable for off-road terrain. Those descriptions are not included herein.

32. Although vibration was implicated in failures by Teams 2005-05 (see paragraph XIII.B.3.) and 2005-12 (see paragraph XIII.B.6.), only one team reported "mil-spec" connectors (presumably similar to Amphenol-style connectors common to military hardware) were in use by the team: Team 2005-18.

33. See Appendix C for a list of important dates and milestones for the 2004 and 2005 GCE.

34. Inadequate test and evaluation was the leading cause of failure during the 2005 GCE among potentially disruptive teams, suggesting that even if a greater number of teams were potentially disruptive, inadequate test and evaluation may have prevented them from being competitive with Teams 2005-13, 2005-14, and 2005-16, all of which had prior experience and extensive corporate or academic sponsorship. See paragraph XV.E. GPS "jump" and position error was the problem most frequently reported by the teams which was preventable through adequate test and evaluation.

35. The hyperlink to the Team 2005-07 technical proposal hosted by the Archived Grand Challenge 2005 website ([19]) was a hyperlink to the team website, and the author was unable to locate a copy of the Team 2005-07 technical proposal on the team website. As a result, the author concluded the technical proposal was unavailable for review. See paragraph V.C.32.

36. Team 2005-12 later stated: "...[The challenge vehicle] suffered a communications failure between the GPS unit and the guidance computer just before Beer Bottle Pass, a mountain pass near the end of the course, that would have ended a fully autonomous attempt." ([183], p. 753). Obviously, a similar communications failure during the 2005 GCE would have resulted in a similar outcome. However, the author is here attempting to distinguish between potentially-disruptive teams and other teams, and there is no evidence supporting a conclusion a similar communications failure would have occurred during the 2005 GCE if Team 2005-12 had not failed to complete the 2005 GCE due to the programming error reported.

37. This observation and similar observations became the basis for a recommendation to develop a process called "acclimation" whereby the challenge vehicle controlling intelligence would calibrate itself. This would make the controlling intelligence portable between vehicles. The recommendation is discussed in more detail in the thesis for which this technical report is the foundation.

38. The author also considered the possibility that lack of sponsorship was ultimately the cause of Team 2004-16 / 2005-17 failure to complete the 2005 GCE. However, although Team 2004-16 / 2005-17 did not report a 2004 or 2005 GCE budget, the team reported moderate corporate and academic sponsorship during both the 2004 and 2005 GCE.

Anecdotal evidence, specifically estimated new vehicle cost based on used vehicle sales, supports a conclusion the cost of the vehicle selected as challenge vehicle platform by Team 2004-16 / 2005-17 during the 2005 GCE would have exceeded $8000. The author asserts Team 2004-16 / 2005-17 would have been able to procure a used commercially-available SUV or truck capable of completing the 2005 GCE at this cost.

However, available estimates of the "EMC AEVIT DARPA Special Edition Package" indicated the cost of the vehicle control system was $35,000 ([215]), which would be an investment several times the cost of the challenge vehicle itself. The author was unable to independently verify either the cost of the Team 2004-16 / 2005-17 challenge vehicle platform during the 2005 GCE or the cost of the "EMC AEVIT DARPA Special Edition Package" because pricing information is not part of the published record. See Chapter XVI.

The author concluded insufficient information was available to determine if lack of sponsorship was ultimately the cause of Team 2004-16 / 2005-17 failure to complete the 2005 GCE, although he accepts it is a possibility.

39. Teams are listed in alphabetical order, based on the alphabetizing scheme used by DARPA ([254]), in which the words "a", "an", or "the" are not considered to be part of the scheme. DARPA established an alternate alphabetizing scheme, which treats the word "team" as "a", "an" or "the" ([242]). The original alphabetizing scheme was retained so that the teams would appear in the same order when referenced herein.

In addition, to preserve alphabetical order, the occurrence of the team names "MonsterMoto" and "Mojavaton", in the order presented by DARPA ([242]), was reversed.

40. Team 2004-09 reported a "stock four-wheel drive vehicle" was in use by the team ([47], p. 2). However, the "Team Information" provided by DARPA via the Archived Grand Challenge 2005 website ([19]) reported the Team 2004-09 challenge vehicle was a purpose-modified 2004 Acura MDX.

41. Team 2004-13 reported a "4-wheel drive vehicle" was in use by the team ([232], p. 1). Team 2004-13 participated in the 2005 GCE as Team 2005-15. Team 2005-15 reported the team challenge vehicle was a purpose-modified 2003 ATV Prowler ([53], p. 4).

42. The hyperlink to the Team 2005-07 technical proposal hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) was actually a hyperlink to the team website. The author was unable to locate a copy of the Team 2005-07 technical proposal on the team website. As a result, the author concluded the technical proposal was unavailable for review. See paragraph V.C.32. However,

Team 2005-07 reported the team challenge vehicle was a purpose-modified 1987 Chevrolet Suburban ([233]).

43. DARPA reported the number of miles of the 2005 GCE course completed by each team which participated in the 2005 GCE ([37]). The number of miles reported ([37]) does not conform to either the reported length of the 2005 GCE course[15] or the calculated length. See paragraph II.C.1.b. The reported length of 131.6 miles plus the smallest possible increment greater than the reported length (0.1 miles) may indicate course completion.

44. Although the presentation itself is undated, file "overview_pres.pdf" hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) is dated December 12, 2003.

45. Although the copy of DARPA's responses is undated, file "darpaanswersgeneral11-26-03.pdf" hosted by Team 2004-20 via the Team 2004-20 website ([20]) is dated November 26, 2003.

46. Although the presentation itself is undated, file "qidprocessdescription.pdf" hosted by Team 2004-20 via the Team 2004-20 website ([20]) is dated January 2, 2004.

47. The title of this reference cited by Auburn University ([262]) does not match the title of the reference itself: "Development of an Autonomous Vehicle for the DARPA Grand Challenge".