CHAPTER V. TOTAL COST

V.A. Discussion

Section 2374a of Title 10 of the United States Code ([60]) authorized the Secretary of Defense: “acting through the Director of Defense Research and Engineering and the service acquisition executive for each military department, may carry out programs to award cash prizes in recognition of outstanding achievements in basic, advanced, and applied research, technology development, and prototype development that have the potential for application to the performance of the military missions of the Department of Defense.”[19]

Section 220 of House Report 106-945 (“Enactment of Provisions of H. R. 5408, The Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001”) stated, in part: “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]). Section 220(d)(4) defines the term “operational ground combat vehicles”: “The term 'operational ground combat vehicles' means ground combat vehicles acquired through the Future Combat System acquisition program of the Army to equip the future objective force, as outlined in the vision statement of the Chief of Staff of the Army.”

As of March 2, 2009, the U. S. Army stated the Future Combat System (FCS) Brigade Combat Team (BCT) systems included: “Two classes of unmanned ground vehicles, the XM1216 Small Unmanned Ground Vehicle (SUGV), and Multifunction Utility/Logistics and Equipment Vehicle (MULE) variants” ([61]).

The FCS was a modernization-through-acquisition program[20]. Department of the Army Fiscal Year (FY) 2009 Budget Estimates ([64]) did not report per-unit costs for the three planned Multifunction Utility/Logistics and Equipment Vehicle (MULE) variants. However, it is unlikely the production cost of the basic MULE variant, the XM1217 MULE-Transport (MULE-T) ([65]), would have far exceeded the current production cost of the High Mobility Multipurpose Wheeled Vehicle (HMMWV).

Production cost estimation information for several “generations” of HMMWV is available, including the current base model M1097A2 “heavy variant” and the “up-armored” M1151A1/M1152A1:

- The Department of Defense FY 2009 Budget Request Summary Justification ([66]) stated the Department of Defense plans to acquire 5249 units at a total cost of $989.7 million, for an average unit cost of approximately $189,000. However, this figure includes procurements of advanced models based on the Extended Capacity Vehicle (ECV2) Chassis with unit costs ranging from $134,000 to $248,000, which increases the average unit cost.

- The Department of the Army Fiscal Year (FY) 2009 Budget Estimates ([64]) reported a "Unit Cost" of $168,000 for the "Armored" version of the M1151A1, and $103,000 and $129,000 for the "Armor Ready" and Armored versions, respectively, of the M1152A1, and $150,000 for the Armored version of the M1165A1. These models comprise the bulk of FY 2009 procurement, and represent 4126 of 5065 units procured, with an average unit cost of approximately $148,000. From FY 2007 to FY 2009 the unit cost for these units increased by $2000 to $3000 for each version. Prior years' data indicated procurement of 122,522 units with a total "Gross Cost" of $7,420.4 million, for a unit cost of approximately $61,000. However, this unit cost includes prior models such as the M998 and M1097A2 which were less expensive than the current up-armored variants.

- At the 2003 Tactical Wheeled Vehicles Conference the Army National Guard (ARNG) reported a unit cost of $77,000 for the HMMWV ([67]). This is most likely the M1097A2 which was based on the A2 series modification package introduced in 1995, and which figures prominently in the FY 2003 budget ([68]), with 752 of 2154 units procured at a unit cost of $63,000. However, it is unclear how the ARNG arrived at a unit cost of $77,000, since the average unit cost for all 2154 units procured in FY2003 was approximately $68,000. During this conference, the ARNG also reported a unit cost of $185,000 for an up-armored HMMWV. As before, it is unclear how the ARNG arrived at a unit cost of $185,000, since the unit cost of the up-armored M1114 variant was $71,000.

- At the 2008 Tactical Wheeled Vehicles Conference the Department of the Army reported a unit cost of $60,000 for the M998 HMMWV and $150,000 for a "UA HMMWV" (up-armored HMMWV) ([69]). These figures correspond roughly with the Department of the Army Fiscal Year (FY) 2009 Budget Estimates prior years' data unit cost of $61,000 and average unit cost of approximately $148,000, respectively.

- And in 2005, the Maine Military Authority estimated the unit cost of a "new basic HMMWV" at "approximately $77,000" ([70]). This number is used to calculate the "Savings Per HMMWV" for vehicles refurbished by the Maine Military Authority from 1997 to 2005, and corresponds to the unit cost of $75,000 and $77,000 for the up-armored M1151 and M1152, respectively, in the FY 2005 budget ([68]).

Based on the available data, the unit cost of a HMMWV will be estimated at $150,000 herein, corresponding to the average unit cost of the models comprising the bulk of FY 2009 procurement.

It is unlikely that the Department of Defense will choose, as its autonomous ground vehicle control technology, a solution the hardware cost of which represents a significant portion of the unit cost of FCS unmanned ground vehicles. Far more likely, in fact, is that the Department of Defense, in an era of declining defense spending and increased global demand for resources, will seek a cost-effective solution.

To offer a sense of perspective, the Abrams Upgrade Program upgrades M1/M1A1 Abrams Main Battle Tanks (MBT) to the M1A2 System Enhancement Package (SEP) configuration. The SEP upgrades both the Gunner's Primary Sight (GPS) and The Commander's Independent Thermal Viewer (CITV) on the M1A2 SEP tank to include the improved thermal imaging capabilities of new Block I 2nd Generation Forward Looking Infra-Red (FLIR) technology. The sights "allow gunners and field commanders to see, identify and target enemy platforms 24 hours a day, regardless of obscurants such as smoke, fog, and dust." The M1/M1A1 MBT "Basic Vehicle" has a FY 2009 unit cost of $3,988,000. The FLIR upgrade has a FY 2009 unit cost of $407,000, or approximately ten percent of the basic vehicle cost ([71]).

Ten percent of the basic vehicle cost is a realistic estimate of the cost of a sensor technology that provides a distinct advantage in combat. Therefore, the author does not anticipate the cost of the sensor technology that provides "semiautonomous and leader-follower capability" to unmanned ground vehicles to exceed ten percent of the basic vehicle cost, or $15,000 of the $150,000 estimated unit cost of the HMMWV.

Neither detailed technical information nor cost information was available from General Dynamics Robotic Systems ([72]), which was awarded the contract for the FCS Autonomous Navigation System (ANS):

> General Dynamics Robotic Systems (GDRS) is responsible for the design, development, manufacture, integration, and testing of the Autonomous Navigation System (ANS) for the Army's Future Combat System (FCS) program. The ANS system is capable of autonomously controlling any of several vehicles designated by the Army, including the Multi-functional Utility Logistics Equipment (MULE) platform, the Armed Reconnaissance Vehicle (ARV), as well as Manned Ground Vehicles (MGVs).
>
> ANS, a major subsystem in the FCS manned combat system, will provide navigational, perception, path-planning and vehicle-following algorithms and the requisite onboard sensor package for autonomous mobility.

V.B. Analysis

V.B.1. Comprehensive review of technical papers for 2004 QID and GCE participants

Although a variety of sensors were in use by teams which participated in the 2004 and 2005 GCE, sensors in use by the teams can broadly be classified as state, environment, and navigation sensors. It is difficult to classify some sensors, such as driveshaft or wheel encoders, because they provide both state (e.g., vehicle or ground speed) and navigation (e.g., incremental distance) information. Other sensors, such as GPS or DGPS receivers, are easier to classify based on their primary purpose as a geolocation sensor, but geolocation estimates reported by GPS or DGPS receivers can also be used to determine state information (e.g., vehicle or ground speed), and some COTS components containing a GPS or DGPS receiver provide reliable estimates of instantaneous or average vehicle or ground speed. These issues were generally resolved as described in paragraphs V.B.3., V.B.5., and V.B.5.b., below.

The author completed a comprehensive review of technical papers submitted by teams participating in the 2004 QID and GCE. In general, this was accomplished by searching for key words related to the sensor technologies in use by the teams, for example: “video”, “camera”, and “stereo” for cameras; or “LIDAR”, “LADAR”, and “laser” for LIDAR sensors. The purpose of this review was to determine if team technical papers reported sufficient technical detail to identify the quantity, manufacturer, and model number for state, environment, and navigation sensors in use by the teams. Based on the state, environment, and navigation sensors identified, the author could then produce a reliable estimate of the total cost of the sensor technology in use by each team, which could be used to answer the following research questions:

- Did the cost of the sensor technology exceed the cost of the platform for which it was designed?
- Was it possible to relatively rank vehicles by use of a metric such as total cost per mile and determine which solutions were more cost effective?
- Was the cost of the sensor technology alone a reliable predictor of success?

V.B.2. Review of 2005 GCE technical papers

The author did not complete a comprehensive review of 2005 NQE and GCE technical papers. The technical papers for teams which participated in the 2005 GCE were reviewed to determine if team technical papers reported sufficient technical detail to identify the quantity, manufacturer, and model number for environment and navigation sensors in use by the teams, and to provide a basis for comparison between results for teams participating in the 2004 and 2005 GCE.

The author did not attempt to determine if 2005 technical papers reported enough information to identify the quantity, manufacturer, and model number for state sensors in use by the teams. DARPA, in establishing the requirements for technical papers submitted by teams expressing interest in participating in the 2004 and 2005 GCE, asked each team to respond to standard questions which were presented in outline format. See Tables XXII and XXIII. Although the standard questions asked by DARPA prior to the 2004 GCE were revised before the 2005 GCE, 2004 GCE Standard Question (SQ) 1.f.1 does not differ significantly from 2005 GCE SQ 2.3.3. In general, teams participating in the 2005 GCE reported less technical detail for state sensors than teams participating in the 2004 QID or GCE.

The author considers this supports conclusions that solutions offered by some teams were unnecessarily complex, that for some teams, excessive attention to detail was evidence of distraction, and that some teams recognized the risk of, and attempted to reduce, complexity where possible. See paragraph XIV.B. The changing problem definition reported by DARPA may also have been a contributing factor. See Appendix C.

V.B.3. Classification of state sensors

For the purposes of classification herein, state sensors are considered to be those sensors which provide information about the state of the challenge vehicle. The author does not consider navigation sensors to be state sensors. See paragraph V.B.5.b. Examples of state sensors include:

- engine RPM (or tachometer) sensors
- brake pressure or brake position sensors
- fuel level sensors
- temperature sensors
- throttle position sensors
- transfer case sensors
- transmission position sensors
- steering angle or steering position sensors

V.B.3.a. <u>Estimation of quantity of state sensors</u>

Where a team reported insufficient technical detail to determine the quantity of state sensors in use by the team, the author estimated the quantity as follows:

- one brake pressure sensor
- one brake position (also “settings”) sensor
- one engine RPM (also “engine running” or “engine condition”) sensor
- one driveshaft RPM sensor
- one intake manifold pressure sensor per intake manifold
- one fuel level sensor
- one water temperature (or radiator temperature) sensor
- one transmission shifter position (or gear position) sensor
- one transfer case position sensor
- one throttle position sensor
- one steering position (or angle or rate) sensor (two if for front and rear steering)
- one oil pressure sensor
- one air conditioning sensor

V.B.4. Classification of environment sensors

For the purposes of classification herein, environment sensors are considered to be those obstacle- and path-detection sensors in use by the teams. Sensors which did not, in the author's estimation, provide the controlling intelligence with useful obstacle- or path-detection information at the 2004 and 2005 GCE average speeds of 22.2 mph and 21.3 mph, respectively, or the maximum “militarily relevant speed” established by DARPA of 20 mph (see paragraph II.C.6.), were not considered environment sensors for the purposes of determining total cost. These sensors were “discounted”, and are denoted by an “X” in the “Sensor Type” column in Tables XXV and XXVII. Examples include:

- ultrasonic (or SONAR) sensors
- touch (or tactile) sensors
- depth sensors
- conductivity (or water) sensors
- ground whiskers or vibration sensors

- photoelectric sensors

Some observations concerning discounted sensors are documented in the paragraphs which follow because they support conclusions which will be discussed in later sections.

V.B.4.a. Clarification of terminology

V.B.4.a.i. Laser range finders

Teams alternately referred to "laser range finder", "scanning laser range finder", and "line scanner" for various environment sensors utilizing lasers, which made it difficult to determine what sensors were in use by some teams. Examples have been noted throughout the text.

V.B.4.b. SICK LMS 291 LIDAR sensor model numbers

Seventeen teams which participated in the 2004 and 2005 GCE referred to SICK "LMS 291" LIDAR sensors, or some variant thereof. Only four teams reported the complete model numbers of the SICK LMS 291 product family LIDAR sensors in use by the team: Teams 2004-12, 2005-02, 2005-08, and 2005-18.

The author notes manufacturer product literature published prior to the 2004 GCE referred to SICK LMS 291-S05 and LMS 291-S14 LIDAR sensors ([73]), while manufacturer product literature published prior to the 2005 GCE referred to a SICK LMS 291-S15 LIDAR sensor ([74]). This inconsistency may explain why teams did not report a complete model number for these sensors. Manufacturer product literature published since the 2005 GCE referred to SICK LMS 291-S05, LMS 291-S14, and LMS 291-S15 LIDAR sensors ([75]).

V.B.5. Classification of navigation sensors

For the purposes of classification herein, navigation sensors are considered to be those which collectively allow the controlling intelligence to determine challenge vehicle geolocation, attitude, and speed. Examples include:

- accelerometers
- gyroscopes
- compasses, digital compasses, or electronic compasses
- magnetometers or "northfinding" modules
- OE, AOE, encoders such as potentiometers or rotary sensors, or wheel speed sensors used in odometry, including differential odometers

- speed sensors
- one- or two-axis inclinometers or sensors which determine challenge vehicle attitude relative to the horizon
- IMU
- INS
- GPS or DGPS

V.B.5.a. Clarification of terminology

V.B.5.a.i. Geolocation

Although DARPA and the teams variously referred to "position", "localization data" or "localization information", and "geolocation", "geolocation" is used exclusively herein to refer to latitude, longitude, and altitude.

V.B.5.a.ii. IMU and INS

The teams and some manufacturers alternately referred to an IMU as an INS, and vice versa. The author draws a clear distinction between an IMU and an INS: an IMU provides attitude data only: rotation (roll, pitch, and yaw) and acceleration in three axes; an INS estimates geolocation after initialization, typically using GPS, based on navigation data from other sensors, such as an IMU, odometry, and magnetic compass.

For example, the ISI ISIS-IMU is an INS, even though ISIS-IMU includes the acronym "IMU" in its name (see paragraph V.C.18.c.).

V.B.5.a.iii. Speed

The teams variously referred to "speed", "vehicle speed", "ground speed", "velocity", and "velocity state". All of these terms are used herein to refer to the vehicle or ground speed in the direction the vehicle is traveling.

V.B.5.b. Navigation sensors do not provide state information, and they are not state sensors

Navigation sensors do not provide state information, and they are not state sensors. This is inconsistent with the interpretation of some teams.

Responses to 2004 GCE standard questions revealed some teams included interpretation of navigation data in the state sensing sections, and vice versa. For some teams, this was due to the use of a COTS IMU or INS which provided navigation data such as heading, speed, roll, pitch, and yaw, and for others because their sensor integration solution fused a combination of inputs from navigation sensors such as compasses, gyroscopes, and odometers into a custom INS developed by the team. For example:

- Team 2004-02

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-02 stated: "[The challenge vehicle] will use the American GNC Coremicro Land Navigator (LN) AHRS/DGPS/INS system to determine the geolocation of [the challenge vehicle]. Heading, roll, and pitch will be introduced into [the challenge vehicle's] computer systems through the Coremicro's serial port (RS232) interface to the servers." ([9], p. 9).

- Team 2004-08

In a section titled "State Sensing", Team 2004-08 stated: "The truck's speed is sensed by POS LV." ([76], p. 5). This is a reference to the Applanix POS LV, which is a geolocation sensor not specifically referred to in the Team 2004-08 technical paper "Localization" section. The POS LV is referred to as a "specific device" in the "Processing" section of their technical paper, which provides input into the team's sensor integration solution: "The computer, which will be used for high level route planning, will use GPS and INS inputs. The device being used contains both GPS and INS internally. It will run off of the INS with updates to the current location using the GPS when available. The specific device is model number POS LV built by Applanix Corporation." ([76], p. 3).

- Team 2004-09

In a section titled "External Sensors", Team 2004-09 stated: "The vehicle state includes engine speed, wheel rotation speed, ground speed, current direction and current steering wheel position. In addition, sensors will provide vehicle attitude with respect to the horizon and 3-axis acceleration. The EMC AEVIT system interfaces with the vehicle control module providing some of these parameters. Additional sensors will be identified or designed to provide the rest." ([47], p. 7).

- Team 2004-10

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-10 stated: "Vehicle state is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), current and voltage sensors. Vehicle state is reported by GPS (latitude, longitude, and altitude), vehicle Pose (roll, pitch, yaw), and vehicle velocity. Onboard software calculates vehicle's speed and acceleration." ([77], p. 4).

V.B.5.c. Estimation of quantity of navigation sensors

Where a team reported insufficient technical detail to determine the quantity of navigation sensors in use by the team, the author estimated the quantity as follows:

- one heading sensor
- one accelerometer
- one wheel rotational position sensor per wheel or axle, as described by the team

V.B.6. Corrections and standardization

In general, corrections were made to manufacturer names and model numbers reported by the teams where the author was able to determine they were in error, and to standardize the use of acronyms. Corrections have been noted throughout the text. These corrections are reflected in Tables XXIV, XXV, XXVI, XXVII, XXVIII, and XXIX. Table XXXV provides a list of acronyms used herein.

V.B.7. Elimination of state sensors from total cost

After a preliminary analysis, it was evident that team technical papers reported the least identifying information for state sensors. See Table XXIV. Available cost information indicated that many state sensors are low-cost. In general, environment and navigation sensors are much more expensive. As a result, the author concluded it may be possible to produce a reliable estimate of the total cost of the sensor technology in use by each team using the cost of environment and navigation sensors only.

V.B.8. Known, unknown, and estimated sensors

In the paragraphs which follow (see paragraphs V.C. and V.D.), the author uses the words "known", "unknown", and "estimated" to classify sensors described by 2004 and 2005 technical papers. In general, a sensor was considered "known" if the author was able to identify the quantity, manufacturer, and model number of the sensor in use by review of published records (see Chapter XVI.). If either the quantity, manufacturer, or model number could not be determined by review of published records, the author concluded the sensor was "unknown", and the specific reason the author was unable to determine the quantity, manufacturer, or model number was reported.

Because they do not contribute additional cost to procure, all OEM sensors (i.e., sensors which were part of the challenge vehicle) were considered known.

Teams which participated in the 2004 QID and GCE did not generally publish their results following the 2004 GCE, and review of published records for teams which participated in the 2005 GCE indicated that there was a significant difference between the configuration of the challenge vehicle described by some team technical papers prior to the 2005 GCE and the configuration described by published records after the 2005 GCE. Sixteen teams which participated in the 2005 GCE published their results via the Journal of Field Robotics; twelve of which also participated in the 2004 GCE. As a result, the published record for the 2005 GCE is more complete. Where necessary, the author has attempted to err on the side of "most conservative", based on a review of the published record.

V.C. Resolution of discrepancies in the published record

In the course of performing the review, the author was required to resolve many discrepancies in the published record to identify the quantity, manufacturer, and model number for environment and navigation sensors in use by the teams. The paragraphs which follow support that resolution, as noted, where published records conflict or are self-contradictory, and provide justification for the information presented by Tables XXIV, XXV, XXVI, XXVII, XXVIII, and XXIX. The author acknowledges the possibility that additional information may be available from published records which the author was unable to review while documenting the results of this analysis.

Where the words "in use by the team", or words to that effect, are used herein, they mean in use by the team during the 2004 QID, 2004 GCE, or 2005 GCE if the team participated in those events. The words "during the 2005 GCE", or words to that effect, are used herein if necessary to highlight a difference between the technical paper and final written report.

V.C.1. Team 2004-01

- The Team 2004-01 website reported limited additional identifying information for the sensors in use by the team.
- Team 2004-01 passed on their turn on the first day of the 2004 QID ([78]), and terminated within the starting chute area on the last day of the 2004 QID ([79]).
- Team 2004-01 was not selected to participate in the 2004 GCE ([80]).

V.C.1.a. Unknown other sensors

Team 2004-01 stated: "Other sensors monitor engine RPM, intake manifold pressure, brake settings, brake hydraulic pressure, fuel level, water temperature, individual wheel speed, transmission gear position, throttle position, and steering angle[.]" ([8], p. 4), but reported no additional identifying information for the "other sensors" in use by the team. The author estimated the quantity of state and navigation sensors in use by Team 2004-01 in accordance with paragraphs V.B.3.a. and V.B.5.c., but otherwise considers these sensors unknown.

V.C.1.b. Unknown cameras

Team 2004-01 stated: "Two cameras will be used. For color analysis a Fire wire digital camera with 1280 x 980 resolution will be used. For texture analysis a monochrome camera, sensitive to near IR will be used." ([8], p. 3), but reported no additional identifying information. The author concluded one camera of each type was in use by Team 2004-01, but otherwise considers these sensors unknown.

V.C.1.c. Unknown SICK LIDAR sensors

Team 2004-01 alternately stated: "Two Sick LMS211 LIDAR units will scan a 100-degree field of view in front of the vehicle providing terrain contour data." ([8], p. 3) and "The laser scanner is a Sick LMS220." ([8], p. 9), but reported no additional identifying information.

Photographs of the challenge vehicle hosted by Team 2004-01 via the Team 2004-01 website ([81]) revealed two LIDAR units were in use by the team. Both the SICK LMS 211-30106 and 211-30206 have a scanning angle of 100 degrees ([74]); the SICK LMS 220-30106 has a scanning angle of 180 degrees ([73]).

The author concluded either two SICK LMS 211-30106 or two SICK LMS 211-30206 LIDAR sensors were in use by Team 2004-01, in lieu of one SICK LMS 220, and considers the manufacturer of these sensors known, but model number unknown.

V.C.1.d. Unknown ultrasonic sensors

Team 2004-01 stated: "Close range ultrasonic sensors will be mounted around the perimeter of the vehicle, at wheel level, to provide 360-degree hazard detection at crawl speeds when other sensors are inoperative or unable to see." ([8], pp. 3 - 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.1.e. Unknown gyroscopes and unknown accelerometers

Team 2004-01 stated: "The vehicle uses 3 axis rate gyros and 3 axis accelerometers to determine attitude and speed changes." ([8], p. 4), but reported no additional identifying information. The author considers the gyroscopes and accelerometers in use by Team 2004-01 unknown.

V.C.1.f. Unknown compass

Team 2004-01 stated: "The odometry system uses odometry, inertial, GPS, and digital compass data to determine its location." ([8], p. 4), but reported no additional identifying information. Throughout the team technical paper ([8]), Team 2004-01 variously referred to a "compass", "digital compass", or "electronic compass". The author concluded one compass was in use by Team 2004-01, but otherwise considers this sensor unknown.

V.C.1.g. Trimble AgGPS 114

Team 2004-01 stated: "The DGPS receiver is a Trimble AGPS 114." ([8], p. 4). Trimble did not manufacture a DGPS receiver with model number "AGPS 114"; the corresponding model number was "AgGPS 114" ([82]). The author concluded "AGPS 114" was an error, that one Trimble AgGPS 114 was in use by Team 2004-01, and considers this sensor known.

V.C.2. Team 2004-02

- Team 2004-02 participated in the 2005 GCE as Team 2005-01. See paragraph V.C.26.
- The Team 2004-02 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-02 website reported no additional identifying information for the sensors in use by the team.
- Team 2004-02 partially completed the 2004 QID course on the second and third day of the 2004 QID ([84] and [85]), and completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-02 was selected to participate in the 2004 GCE ([80]).

V.C.2.a. Unknown state sensors

In response to 2004 SQ 1.c.2 (see Table XXII), Team 2004-02 stated: "Some of the above-mentioned sensors are used to sense the state of [the challenge vehicle]." ([9], p. 7). This appears to be a reference to Figure 2 ("System hardware configuration") of the team technical paper ([9], p. 6), which lists several environment and navigation sensors.

Team 2004-02 did not report sufficient technical detail to determine what environment and navigation sensors were in use by the team to sense the state of the challenge vehicle or what state information they provide, and the author does not consider navigation sensors to be state sensors (see paragraph V.B.5.b.). As a result, the author considers these sensors unknown.

V.C.2.b. OBD-II

Team 2004-02 stated: "ODB-II Information: Utilizing the ability for a 1994 Jeep Grand Cherokee to attempt to deliver vehicle data to a COTS monitor has proven to be less than useful information. The team continues to do cost analysis of the race use of this information." ([9], p. 12).

The author concluded Team 2004-02 was referring to information provided by the OEM On-Board Diagnostic (OBD) system, commonly referred to as OBD-II, in lieu of "ODB-II". The author considers all OEM sensors known (see paragraph V.B.8.). However, Team 2004-02 did not report sufficient technical detail to determine what "vehicle data" OBD-II provided.

V.C.2.c. Team 2004-02 MetalSense B1 touch sensors

In response to 2004 SQ 1.e.2 (see Table XXII), Team 2004-02 stated: "Three touch sensors will be mounted in the front of the vehicle." ([9], p. 9). However, via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8) Team 2004-02 reported that four "MetalSense B1" touch sensors were mounted on the challenge vehicle. Neither the Team 2005-01 technical paper ([10]) nor the team website ([86]) reported touch sensors were in use by the team, or reported additional, clarifying information. The author concluded four Team 2004-02 MetalSense B1 touch sensors were in use by Team 2004-02, and considers these sensors known; the difference in cost between three and four touch sensors is not expected to be significant.

V.C.2.d. Point Grey Bumblebee cameras

Team 2004-02 alternately stated three and four Point Grey Bumblebee cameras were in use by the team. In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-02 reported three Bumblebee cameras were in use by the team via an un-numbered table of computer hardware ([9], p. 5). Via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8), Team 2004-02 reported four Bumblebee cameras were in use by the team.

Via Table 1 ("Computing Hardware") and Figure 4 ("Sensing & Stopping Distances") of the Team 2005-01 technical paper ([10], pp. 4 and 9), Team 2005-01 reported five Bumblebee cameras were in use by the team. Via the team website, Team 2005-01 stated: "[The challenge vehicle] uses Bumblebee stereo vision cameras for obstacle detection." ([86]), but reported no additional identifying information. The author concluded a different quantity of Bumblebee cameras were in use by Team 2005-01 than were in use by Team 2004-02.

The author estimated the quantity of Bumblebee cameras in use by Team 2004-02 to be three, but otherwise considers these sensors known.

V.C.2.e. FLIR A20M and unknown AVT camera

Via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8), Team 2004-02 reported one FLIR A20M and one "Allied Vision Systems Dolphin" color camera were in use by the team. The use of these descriptions is consistent throughout the text of the technical proposal, with the exception of Figure 2. Figure 2 ("System hardware configuration") of the team technical paper ([9], p. 6) reported two "EMX

Raytheon Thermal Cameras" were in use by the team; Figure 2 did not report either the FLIR A20M or color camera were in use by the team. The author concluded the EMX Raytheon Thermal Cameras were not in use by Team 2004-02, and considers the FLIR A20M in use by the team known.

The author was unable to locate a manufacturer named "Allied Vision Systems" with a "Dolphin" color camera product, but a manufacturer named "Allied Vision Technologies GmbH" exists. AVT had a product line named "Dolphin", which has since been discontinued ([87]). The Dolphin product line had multiple model numbers with different capabilities: "F-145B/C" and "F-201B/C" ([88]). These model numbers now correspond to the "Pike" and "Marlin" product lines, respectively.

The author concluded one AVT camera was in use by Team 2004-02, but considers the model number of this sensor unknown.

V.C.2.f. Epsilon Lambda ELSC71-1A

Team 2004-02 stated: "One other terrain sensor [Team 2004-02] is using is a 77 GHz three dimensional tracking obstacle detection RADAR. This sensor is built by Epsilon Lambda Electronics (Model #ELSC71-1B)..." ([9], p. 8).

No RADAR with model number "ELSC71-1B" exists, and the author was otherwise unable to locate manufacturer product literature for the Epsilon Lambda ELSC71-1B ([89]). However, the capabilities reported by Team 2004-02 for the ELSC71-1B do not differ significantly from the capabilities of the Epsilon Lambda ELSC71-1A, and the description reported by Team 2004-02 is virtually identical to the manufacturer's description of the ELSC71-1A. Review of 2004 technical papers revealed the ELSC71-1B was not in use by any other team, but the ELSC71-1A was in use by three other teams.

The author concluded "ELSC71-1B" was an error and that one Epsilon Lambda ELSC71-1A was in use by Team 2004-02, and considers this sensor known.

V.C.2.g. AGNC Land Navigator

Via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8), Team 2004-02 reported an "American GNC coremicro UNUCN1" was in use by the team. Throughout the text of the technical proposal, Team 2004-02 referred to the "American GNC Coremicro Land Navigator". Figure 2 ("System hardware configuration") of the Team 2004-02 technical paper ([9], p. 6) reported an "AGNC CoreMicro GPS/INS" was in use by the team, but reported no additional identifying information. An alternate INS was in use by Team 2005-01 during the 2005 GCE.

AGNC does not manufacture a product with a model number "UNUCN1" ([90]). AGNC manufactures several "Universal Navigation and Control Units" (UNCU), and model number UNCUN1 includes a GPS chipset. AGNC stated: "Based on AGNC's coremicro IMU and proprietary GPS/IMU integration technology, the Land Navigator is designed for land navigation." ([90]). Information reported by manufacturer product literature was of limited utility. For example, the author was unable to determine if the AGNC Land Navigator requires the use of an external GPS or DGPS antenna. Team 2004-02 did not report an external GPS or DGPS antenna was in use by the team.

AGNC reported the current AGNC "Palm Navigator" product series is a "wrapper" around the UNCUN1, which itself is a wrapper around a UNCU, which is a wrapper around the coremicro IMU ([91]). The author concluded the AGNC Land Navigator was also a wrapper around the UNCUN1 and that the AGNC Land Navigator was in use by Team 2004-02, and considers this sensor known.

V.C.3. Team 2004-03

- The Team 2004-03 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- Various sources direct the public to three different domains for Team 2004-03 information: www.roboticinfantry.com ([92], p. 1), www.insidiarobot.com ([92], p. 3), and www.ghostriderrobot.com ([17]). Only the latter is currently active, although the others may have been valid at the time of the 2004 QID and GCE. Neither of the other two domains are currently accessible from the Internet, although the domain www.roboticinfantry.com was used to host the Team 2004-03 website through 2007 ([93]). The current Team 2004-03 website reported no additional identifying information for the sensors in use by the team.
- Team 2004-03 passed on their turn on the second day of the 2004 QID ([84]), and terminated their attempts on the third day of the 2004 QID ([85]), but did not withdraw.
- Team 2004-03 was selected to participate in the 2004 GCE ([80]). On the day of the 2004 GCE, Team 2004-03 officially withdrew prior to start [30].

V.C.3.a. Unknown AOEs and unknown potentiometer

Team 2004-03 stated: "Steering position is determined by an Absolute Optical Encoder (AOE) and a potentiometer. Wheel rotational positions are determined by AOEs." ([92], pp. 5 - 6), but reported no additional identifying information. The author estimated the quantity of AOEs in use by Team 2004-03 in accordance with paragraphs V.B.3.a. and V.B.5.c., but otherwise considers these sensors unknown.

V.C.3.b. Unknown Cognex cameras and unknown other camera

Throughout the team technical paper, Team 2004-03 referred to an indeterminate quantity of "cameras" ([92], pp. 4, 5, and 7). Via the team website, Team 2004-03 stated: "The are two types of cameras used onboard. First, a pair of high resolution 1600x1200 ethernet cameras manufactured by Cognex used for creating realtime 3D scene of the obstacles in front of the vehicle. Second a single CCD, high speed (40 Hz), color camera is used for road detection." ([94]). Team 2004-03 reported no additional identifying information for the cameras in use by the team.

The author concluded two Cognex cameras were in use by Team 2004-03, but considers the model number of these sensors unknown; and concluded one color camera was in use by Team 2004-03, but otherwise considers this sensor unknown.

V.C.3.c. Unknown DGPS receiver

Throughout the team technical paper ([92]) Team 2004-03 referred to "GPS" and "DGPS", but reported no additional identifying information for the DGPS receiver in use by the team. Via the team website, Team 2004-03 stated: "Beyond DGPS, we are using only high speed camera as sensor input." ([94]), but reported no additional identifying information for the DGPS receiver in use by the team. The author concluded one DGPS receiver was in use by Team 2004-03, but otherwise considers this sensor unknown.

V.C.3.d. Unknown Crossbow gyroscopes

Team 2004-03 stated: "The attitude of the vehicle is determined by two Crossbow MEMS gyro [*sic*] (VG 400, AHRS400)." ([92], p. 5). Crossbow reported "VG400" and "AHRS400" were function and series designators ([95]) for products which have since been discontinued, and neither VG400 nor AHRS400 is a complete model number ([96]). The author considers the quantity and manufacturer of these sensors known, but model numbers unknown.

V.C.3.e. Unknown Crossbow IMU

Team 2004-03 stated: "Crossbow Inertial Measurement Unit (IMU) integrated Kalman filter and angular bias elimination to provide direct roll, pitch and heading angles." ([92], p. 4), but reported no additional identifying information. Crossbow manufactures several models of IMU ([95]). Crossbow reported at least five products with different function and series designators have an integrated Kalman filter and either integrated GPS or GPS as an option ([96]): NAV420, VG440, AHRS440, NAV440, and AHRS500. Although Crossbow has since discontinued products which were available at the time of the 2004 QID and GCE, the author considers it likely that multiple products with the capabilities reported by Team 2004-03 were available at the time of the 2004 QID and GCE, and concluded one Crossbow IMU was in use by Team 2004-03, but considers the model number of this sensor unknown.

V.C.4. Team 2004-04

- Team 2004-04 participated in the 2005 GCE as Team 2005-02. See paragraph V.C.27.

- The Team 2004-04 website was updated prior to the 2005 GCE and reflects the challenge vehicle configuration during the 2005 GCE.

- Team 2004-04 had an unsuccessful attempt to start due to instrumentation problems on the first day of the 2004 QID ([78]), nearly completed the 2004 QID course on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).

- Team 2004-04 was selected to participate in the 2004 GCE ([80]).

Team 2004-04 stated: "[The challenge vehicle perception system] consists of a suite of sensor hardware including a fixed SICK LADER [*sic*], a 3D SICK LADAR, three (3) video cameras, three (3) short range radar units, a long range radar unit, and a Videre Design stereo vision system." ([44], pp. 5 - 6).

Team 2004-04 also stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include a NavCom Starfire 2050 GPS, a Garmin WAAS GPS, a quadrature shaft encoder, and a Smiths Industries Northfinding Module, an inertial/magnetic orientation sensor." ([44], pp. 9 - 10).

V.C.4.a. <u>Honeywell ML500PS1PC pressure transducer</u>

Team 2004-04 alternately stated: "Honeywell pressure transducers read the brake pressure..." ([44], p. 9), and "The brake system is also equipped with a Honeywell pressure transducer, ML500PS1PC..." ([44], p. 1). Although the author does not consider the cost of a pressure transducer to be significant, Team 2004-04 reported that both one and more than one pressure transducer were in use by the team. The author estimated one Honeywell ML500PS1PC was in use by Team 2004-04 in accordance with paragraph V.B.3.a., but otherwise considers this sensor known.

V.C.4.b. <u>Unknown Videre Design stereo camera pair</u>

Videre Design manufactures multiple "Stereo System Products", each with a unique model number and capabilities, some of which have been discontinued ([97]). The author concluded one Videre Design stereo camera pair was in use by Team 2004-04, but considers the model number of this sensor unknown.

V.C.4.c. Unknown other cameras

In addition to the stereo camera pair, Team 2004-04 alternately referred to three “cameras”, “video cameras”, “additional cameras”, and “stationary cameras” throughout the team technical paper ([44]), but reported no additional identifying information for the cameras in use by the team.

The author considers it likely Team 2004-04 was referring to the same three cameras, and concluded three other cameras were in use by Team 2004-04, but otherwise considers these sensors unknown.

V.C.4.d. Unknown PRECO RADAR and unknown long-range RADAR

Team 2004-04 alternately stated: “Due to their limited 26-foot range, the three short-range radar units will act collectively as a virtual bumper switch providing a last line of defense to prevent the [the challenge vehicle] from colliding with obstacles in its path.” and “The long-range radar unit provides additional information to the arbiter on free or blocked space. The PRECO Preview long range RADAR system provides range data at distances up to 100 feet.” ([44], p. 6).

Team 2004-04 did not report the model number for either the “short-range” RADAR or Preco PreView RADAR in use by the team ([44]). At least three different product families exist: “Standard PreView” (model numbers SPV 2010, SPV 2015, and SPV 2020 with 10-, 15-, and 20-ft “detection range”, respectively) ([98]), “Xtreme PreView” (model numbers XPV 4020, XPV 4026, and XPV 4032 with 20-, 26-, and 32-ft “coverage”, respectively) ([99]), and “High Resolution PreView” (model numbers HRPV 3010, HRPV 3015, and HRPV 3020 with 10-, 15, and 20-ft “coverage”, respectively) ([100]). No Preco PreView unit has a range of 100 ft, and the use of three matched sensors is consistent with automotive anti-collision RADAR, or short-range RADAR, not long-range RADAR.

The author concluded three Preco RADAR sensors were in use by Team 2004-04, but considers the model number of these sensors unknown, although the “limited 26-foot range” of the “short-range radar units” described by Team 2004-04 matches the 26-ft coverage of Preco PreView XPV 4026.

The author concluded one long-range RADAR sensor was in use by Team 2004-04, but otherwise considers this sensor unknown.

V.C.4.e. Unknown Garmin GPS receiver

Team 2004-04 stated: “[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include ... a Garmin WAAS GPS...” ([44], p. 9), but reported no additional identifying information.

Garmin manufactures dozens of GPS receivers with unique model numbers and capabilities ([101]). The author concluded one Garmin GPS receiver was in use by Team 2004-04, but considers the model number of this sensor unknown.

V.C.4.f. Unknown NavCom GPS receiver

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include a NavCom Starfire 2050 GPS..." ([44], p. 9), but reported no additional identifying information.

The NavCom StarFire SF-2050 GPS receiver and StarFire network were in use by 12 of 40 NQE semifinalists ([102]) and 6 of 23 GCE finalists ([103]). At least two different model numbers of NavCom StarFire GPS receiver existed at the time of the 2004 QID and GCE, and they targeted different markets: "The SF-2050G is designed for backpack GIS and mapping applications while the SF-2050M is ideal for vehicle mounting to suit a wide variety of machine guidance and control applications." ([104]). NavCom launched both the SF-2050G and SF-2050M receivers in 2002 ([105]). The author concluded one NavCom GPS receiver was in use by Team 2004-04, but considers the model number of this sensor unknown.

V.C.4.g. Unknown quadrature shaft encoder

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include ... a quadrature shaft encoder..." ([44], p. 9), but reported no additional identifying information. The author concluded one quadrature shaft encoder was in use by Team 2004-04, but otherwise considers this sensor unknown.

V.C.4.h. Smiths Aerospace North Finding Module

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include a ... Smiths Industries Northfinding Module..." ([44], p. 9), but reported no additional identifying information. The author was unable to locate a manufacturer named "Smiths Industries", but a manufacturer named "Smiths Aerospace" existed at the time of the 2004 QID and GCE, and has since been acquired by GE. The author concluded one Smiths Aerospace North Finding Module was in use by Team 2004-04, and considers this sensor known.

V.C.5. Team 2004-05

- The Team 2004-05 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-05 website was no longer available.

- Team 2004-05 was delayed awaiting parts for the challenge vehicle until the third day of the 2004 QID ([85]), and officially withdrew on the last day of the 2004 QID ([79]).

- Team 2004-05 was not selected to participate in the 2004 GCE.

V.C.5.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-05 reported a list of state sensors in use by the team, including the quantity of each sensor in use, but reported no additional identifying information ([45], p. 5). The author considers the quantity of these sensors known, but the manufacturers and model numbers unknown.

Team 2004-05 stated: "Certain other sensors are present in self regulating systems (i.e [*sic*] alternator, ignition, gps)" ([45], p. 5), but reported no additional identifying information for these sensors. The author considers these sensors unknown.

V.C.5.b. Unknown SONAR sensors

Team 2004-05 stated: "Sonar array: 3 front, 4 per side, 3 rear. 40 kHz. Range 1 -15 ft, cone angle 15 degrees. Purpose: low speed collision avoidance." ([45], p. 4), but reported no additional identifying information. The author concluded fourteen SONAR sensors were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.c. Unknown depth finders

Team 2004-05 stated: "Depth finders: (2) 200 kHz sonic sensor) [*sic*] to detect water depth in front of each wheel." ([45], p. 4), but reported no additional identifying information. The author concluded two depth finders were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.d. Unknown conductivity sensors

Team 2004-05 stated: "Conductivity sensors: (2) for water presence sensing." ([45], p. 4), but reported no additional identifying information. The author concluded two conductivity sensors were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.e. Unknown tactile sensors

Team 2004-05 stated: "Tactile sensors: 3 front, 2 per side, spring loaded, front sensors with single micro switch, side sensor with dual position micro switches. Purpose: front sensors back up for sonar in close range maneuvering. Side sensors to detect and track close range distance to objects like barbed wire and chain link fencing." ([45], p. 4), but reported no additional identifying information. The author concluded seven tactile sensors were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.f. Unknown SICK LIDAR sensors and trinocular camera system

Team 2004-05 referred to both “Main Ladar unit” and “Side Ladar units” in use by the team ([45], p. 4). Via an addendum, Team 2004-05 stated: “Ladar units: 2 SICK LMS 291.” ([45], p. 12). Pages 1 through 11 pre-date pages 12 and 13 of the addendum. However, it is unclear if the addendum referred to either the “Main Ladar unit” or “Side Ladar units” previously described ([45], p. 4), or if the “2 SICK LMS 291” LIDAR sensors were intended to replace both. Paragraph 2.a.4 of the team technical paper ([45], p. 7) referred to a “Ladar system from Laseroptronix”, but it is unclear if this unit was intended to be the main LIDAR unit or if it supplements the SICK LIDAR sensors referred to in the addendum.

In response to 2004 SQ 2.a.1 (see Table XXII), Team 2004-05 referred to a “trinocular camera system”, but reported no additional identifying information ([45], p. 6). This is the only reference to a trinocular camera system made by Team 2004-05.

The “Computational System Block Diagram” ([45], p. 11) is of little help resolving these difficulties because it referred to sensors by type only: “Ladar”, “Radar”, “Sonar”, etc. However, because neither the Laseroptronix LIDAR sensor nor trinocular camera system were referred to in response to 2004 SQ 1.e (see Table XXII), the author concluded the two SICK LIDAR sensors replaced both the “Main Ladar unit” and “Side Ladar units” and considers the quantity and manufacturer of these sensors known, but model number unknown, and concluded no trinocular camera system was in use by Team 2004-05.

V.C.5.g. Unknown Eaton RADAR

Team 2004-05 alternately stated: “Radar unit: (Epsilon Lambda Electronics) Selectable 40/16 degrees azimuth field of view, 2 degrees resolution, range 400 ft. Purpose: detect large obstacles far away, detect and track moving large objects (other vehicles, trains), back up for main Ladar unit.” ([45], p. 4); and via their addendum: “Radar unit: Eaton Vorad VBOX 83001-001 Field of view 12 degrees. Range 300 ft. 2 degrees resolution.” ([45], p. 12).

The “VBOX 83001-001” referred to by Team 2004-05 was part of the “Eaton VORAD Radar Development Toolkit” designed to interface with the Eaton VORAD RADAR antenna ([106]): Team 2004-20 reported their “Eaton VORAD anti-collision radar system” was “a standard Eaton VORAD unit ... interfaced to computers using an Eaton VBOX.” ([107], p. 5).

The author concluded the Epsilon Lambda RADAR was not in use by Team 2004-05, and that one Eaton RADAR was in use by Team 2004-05, but considers the model number of this sensor unknown.

V.C.5.h. Point Grey Bumblebee stereo camera pair

Team 2004-05 stated: "Stereo camera: (Point Grey Bumblebee)" ([45], p. 4), but reported no additional identifying information.

Point Grey had multiple product lines: "Bumblebee", "Dragonfly", "Flea", etc. ([108]). Each product line had multiple model numbers. For example, the two current model numbers for the Bumblebee product line are "Bumblebee 2" and "Bumblebee XB3" ([109]).

The Point Grey website requires a login to download technical manuals for their products. The author does not consider access-controlled manufacturer product literature to be part of the published record. See Chapter XVI. Although the author was unable to determine what model numbers were available at the time of the 2004 and 2005 GCE, the Bumblebee 2 was introduced August 23, 2006 ([110]). The author concluded "Bumblebee" was the model number of this sensor during the 2004 and 2005 GCE, and considers this sensor known.

V.C.5.i. Unknown navigation sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-05 reported a list of navigation sensors in use by the team, including the quantity of each sensor in use, but reported no additional identifying information ([45], p. 5). The author considers the quantity of these sensors known, but otherwise considers these sensors unknown.

V.C.5.j. Unknown gyroscopes

Team 2004-05 stated: "One gyro determines yaw rate and in combination with the front wheel speed sensors are [*sic*] used to correct steering maneuvers as well as for odometric localization in areas of poor gps reception." and "Two gyros are used to measure rate of change in vehicle tilt during pitch and roll, inputs also used for stability control." ([45], p. 5), but reported no additional identifying information.

The author concluded two gyroscopes were in use by Team 2004-05: the first to "correct steering maneuvers as well as for odometric localization in areas of poor gps reception" and to "measure rate of change in vehicle tilt during pitch and roll"; and a second to "measure rate of change in vehicle tilt during pitch and roll", but otherwise considers these sensors unknown.

V.C.5.k. CSI Wireless Vector, CSI Wireless DGPS MAX, and unknown DGPS receivers

Team 2004-05 stated: "The primary method of geolocation used during the mission is a system of multiple Differential GPS receivers, including a Real-Time Kinematic receiver (CSI Vector) that is used for heading determination at zero velocity." ([45], p. 5). The CSI Wireless Vector is a DGPS receiver which uses multiple antennas to function as a compass as well as provide position data ([111] and [112]). In response to 2004 SQ 2.g.1 (see Table XXII), via their addendum, Team 2004-05 stated: "A CSI DGPS MAX sensor has been added..." ([45], p. 12). The CSI Wireless DGPS MAX is also a DGPS receiver ([113]). However, it is unclear if the two DGPS receivers were the "multiple Differential GPS receivers" in use by Team 2004-05.

The author concluded one CSI Wireless Vector and one CSI Wireless DGPS MAX were in use by Team 2004-05, and that additional DGPS receivers may have been in use by Team 2004-05, but considers these sensors unknown.

V.C.6. Team 2004-06

- Team 2004-06 participated in the 2005 GCE as Team 2005-03. See paragraph V.C.28.

- The Team 2004-06 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The Team 2004-06 website was no longer available.

- Team 2004-06 had an unsuccessful attempt to start due to instrumentation problems on the first day of the 2004 QID ([78]), partially completed the 2004 QID course on the third day of the 2004 QID ([85]), and completed the 2004 QID course on the last day of the 2004 QID ([79]).

- Team 2004-06 was selected to participate in the 2004 GCE.

V.C.6.a. <u>Team 2004-06 stereo camera pair</u>

In response to 2004 SQ 1.e (see Table XXII), Team 2004-06 stated: "Please refer to Appendix A. No additional sensors will be used." ([114], p. 2). Appendix A of the Team 2004-06 technical paper ([114]) describes a proprietary stereo camera pair similar to commercially-available stereo camera pairs in use by other teams participating in the 2004 GCE. Team 2004-06 reported very little additional identifying information for the components comprising their proprietary stereo camera pair, and no additional identifying information for the cameras in use by the team.

The author considers the proprietary stereo camera pair in use by Team 2004-06 known, but concluded the cost of this sensor cannot be independently determined.

V.C.6.b. Honeywell HMC1002

Team 2004-06 alternately stated: "two Honeywell dual axis compass sensors" ([114], p. 1) were in use by the team and "The compass is a Honeywell HMC-1002" ([114], p. 2). The author estimated one Honeywell HMC1002 two-axis magnetic sensor was in use by Team 2004-06 as a compass, but otherwise considers this sensor known.

V.C.6.c. NavCom SF-2050G

Team 2004-06 stated: "The GPS unit is a Navcom 2050G unit." ([114], p. 2). The author concluded Team 2004-06 was referring to the NavCom SF-2050G, and considers this sensor known.

V.C.7. Team 2004-07

- Team 2004-07 participated in the 2005 GCE as Team 2005-05. See paragraph V.C.30.
- The Team 2004-07 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-07 website reported limited additional identifying information for the sensors in use by the team.
- Team 2004-07 passed on their turn on the first day of the 2004 QID ([78]), and partially completed the 2004 QID course on the second, third, and last day of the 2004 QID ([84], [85], and [79]).
- Team 2004-07 was selected to participate in the 2004 GCE ([80]).

V.C.7.a. Unknown potentiometer

In response to 2004 SQ 1.a.3 (see Table XXII), Team 2004-07 stated: "A potentiometer measures the absolute servomotor position." ([46], p. 2); and in response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-07 stated: "A potentiometer senses the position of the steering column." ([46], p. 7). Team 2004-07 reported no additional identifying information for the potentiometer in use by the team. The author concluded one potentiometer was in use by Team 2004-07, but otherwise considers this sensor unknown.

V.C.7.b. Unknown ground whisker

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated: "One Ground Whisker. This passive sensor consists of a whisker which trails (or bounces) along the ground. The resulting vibration is picked up by a microphone to evaluate ground roughness.” ([46], p. 7), but reported no additional identifying information. The author concluded one ground whisker was in use by Team 2004-07, but otherwise considers this sensor unknown.

V.C.7.c. Unknown SICK LIDAR sensor

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated: “We are evaluating an active SICK ladar mounted at the front of the truck. This ladar system has at least 10 meters range and 180-degree arc of sweep. It is intended to supplement the radar system in detecting positive obstacles. It is not certain yet whether this system will be available for use in the race, so in evaluating this technical paper we would like you to allow for the possibility that the ladar will not be present.” ([46], p. 7), but reported no additional identifying information.

Photographs hosted by Team 2004-07 via the Team 2004-07 website revealed one SICK LIDAR sensor was in use by the team ([115]), but the Team 2004-07 website reported no additional identifying information. The author concluded one SICK LIDAR sensor was in use by Team 2004-07, but considers the model number of this sensor unknown.

V.C.7.d. FLIR Omega

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated one “Indigo Omega Infrared Camera” ([46], p. 7) was in use by the team. Indigo and FLIR completed a merger January 6, 2004 ([116]). The “Product Name” for this camera was “Micron/A10/Omega” ([117]). The author concluded the manufacturer of this sensor was FLIR, and considers this sensor known.

V.C.7.e. Unknown Rotomotion IMU and unknown Rotomotion magnetometer

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated: “Changes in the vehicle’s angular orientation will be measured by a Rotomotion 6-degree-of-freedom inertial measurement unit and a Rotomotion 3-axis magnetometer.” ([46], p. 7), but reported no additional identifying information. The author concluded one Rotomotion IMU and one Rotomotion magnetometer were in use by Team 2004-07, but considers the model numbers of these sensors unknown.

V.C.7.f. Unknown Hall Effect sensor

Team 2004-07 stated: “A magnetic encoder using a Hall Effect sensor measures rotation of the rear axle.” ([46], p. 7), but reported no additional identifying information. The author concluded one Hall Effect sensor was in use by Team 2004-07, but otherwise considers this sensor unknown.

V.C.8. Team 2004-08

- Team 2004-08 participated in the 2005 GCE as Team 2005-07. See paragraph V.C.32.
- The Team 2004-08 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-08 website reported no additional identifying information for the sensors in use by the team.
- In a press release published after Team 2005-07 was selected to participate in the 2005 GCE, Team 2005-07 stated: "...last year [Team 2004-08 was] unable to compete due to lack of funding." ([118]). Team 2004-08 did not participate in the 2004 QID or GCE.

V.C.8.a. Unknown optical sensor

Team 2004-08 stated: "An optical sensor is mounted on the sprocket connected to the steering motor. This sensor detects the presence of gear teeth between the emitter and collector to determine the position of the steering wheel. By counting teeth as they pass through the optical sensor we are able to tell how far the steering wheel is turned left or right." ([76], p. 5), but reported no additional identifying information.

The author concluded one optical sensor was in use by Team 2004-08, but otherwise considers this sensor unknown.

V.C.8.b. Unknown ten-turn potentiometers

Team 2004-08 stated: "The position of the braking linear actuator is determined by a ten-turn potentiometer. We will use the data gathered about the position of the brake pedal to control the amount of pressure applied to the brakes. Both actuators automatically disengage when they reach the end of their travel due to built in limit switches." ([76], p. 5). Team 2004-08 also stated: "The accelerator and brake pedals are pulled down by steel cables, which run through tubes in the engine bay where two linear actuators are mounted." ([76], p. 2).

As a result, the author concluded linear actuators were in use by the team to control both the accelerator and brake pedals, and that these are "both actuators" to which the team referred. Although Team 2004-08 did not affirmatively state the position of the accelerator pedal was also determined by a ten-turn potentiometer, the author concluded one ten-turn potentiometer was also in use to determine the position of the accelerator pedal and concluded two ten-turn potentiometers were in use by Team 2004-08, but otherwise considers these sensors unknown.

V.C.8.c. Laseroptronix LDM 800-RS232 laser range finders

Team 2004-08 stated: “Laser range finders will be mounted on the front, back, and sides of the vehicle... The range finders will be model number LDM 800-RS232 from Laseroptronix...” ([76], p. 5), but did not report the number of laser range finders in use by the team. The author concluded four Laseroptronix LDM 800-RS232 laser range finders were in use by Team 2004-08, one each for the front, back, and sides of the vehicle.

V.C.8.d. Unknown Applanix INS

Team 2004-08 stated: “The specific device is model number POS LV built by Applanix Corporation.” ([76], p. 3), and reported via an un-numbered table (“GPS Outage Duration”) that the model number was “POS LV 320” ([76], p. 6).

Applanix does not currently manufacture a model number “POS LV 320”. Applanix manufactures a model number “POS MV 320” for marine applications ([119]), and several model numbers of the POS LV for land navigation (200, 220, 420, and 610) ([120]).

Although the author was unable to locate a reference to the Applanix POS LV 320 on the Applanix website, one of the results of an Internet search using the key words “+applanix +'pos lv' +320” as the search string is a document titled “POS LV”, which reported the Applanix POS LV 320 was a model number at the time of the 2004 GCE ([121]). This reference has no revision information, no copyright notice, and is not dated. However, the file attributes indicate it was created April 23, 2004, and last modified December 22, 2005. The author considers April 23, 2004 the date of the reference.

The “IARTK”, “PP”, and “DGPS” figures given by the team technical paper ([76]) for the “POS LV 320” do not match the “IARTK”, “PP”, and “DGPS” figures reported by Applanix ([120]) for any current Applanix POS LV model number. The “IARTK”, “PP”, and “DGPS” figures given by the team technical paper ([76]) for the “POS LV 320” substantially match the “IARTK”, “PP”, and “DGPS” figures given by the undated reference ([121]) for the Applanix POS LV 320, but are not identical. The author concluded one Applanix INS was in use by Team 2004-08, but considers the model number of this sensor unknown.

V.C.9. Team 2004-09

- The Team 2004-09 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-09 website was no longer available.

- Team 2004-09 partially completed the 2004 QID course before stopping to make mechanical adjustments on the first day of the 2004 QID ([78]), and partially completed the 2004 QID course on the third and last day of the 2004 QID ([85] and [79]).

- Team 2004-09 was selected to participate in the 2004 GCE ([80]).

Team 2004-09 stated: "[The challenge vehicle] will be using a laser range finding system, a video camera, a gyroscope, GPS, and a vibration sensor to determine the location of the path being taken, location of the vehicle, obstacles in the path, and the condition of the road/path surface." ([47], p. 7).

V.C.9.a. Unknown state and navigation sensors

Team 2004-09 stated: "The vehicle state includes engine speed, wheel rotation speed, ground speed, current direction and current steering wheel position. In addition, sensors will provide vehicle attitude with respect to the horizon and 3-axis acceleration. The EMC AEVIT system interfaces with the vehicle control module providing some of these parameters. Additional sensors will be identified or designed to provide the rest." ([47], p. 7), but reported no additional identifying information.

The author estimated the quantity of state and navigation sensors in use by Team 2004-09 in accordance with paragraphs V.B.3.a. and V.B.5.c., but otherwise considers these sensors unknown.

V.C.9.b. Unknown gyroscope

Team 2004-09 reported no additional identifying information for the gyroscope in use by the team. The author concluded one gyroscope was in use by Team 2004-09, but otherwise considers this sensor unknown.

V.C.9.c. Unknown vibration sensor

Team 2004-09 reported no additional identifying information for the vibration sensor in use by the team. The author concluded one vibration sensor was in use by Team 2004-09, but otherwise considers this sensor unknown.

V.C.9.d. Unknown SICK LIDAR sensor

Team 2004-09 stated: "The laser system will be a LMS 211 or 221 device manufactured by SICK, Inc." ([47], p. 7), but reported no additional identifying information. The author concluded one SICK LIDAR sensor was in use by Team 2004-09, but considers the model number of this sensor unknown.

V.C.9.e. Unknown camera

Team 2004-09 stated: “The video camera is a generic, high-resolution color digital camera...” ([47], p. 7), but reported no additional identifying information. The author concluded one camera was in use by Team 2004-09, but otherwise considers this sensor unknown.

V.C.9.f. MiTAC Navman TU60-D120 and MiTAC Ashtech DG16

Team 2004-09 stated: “The GPS units are NAVMAN TU60-D120 12 channel GPS, ASHTECH DG16, and GARMIN GPS16A...” ([47], p. 8). The Navman GPS product line is currently manufactured by MiTAC ([122]). The author concluded one MiTAC Navman TU60-D120 sensor was in use by Team 2004-09, and considers this sensor known. The Ashtech DG16 was a product of Thales Navigation. Through a series of mergers and acquisitions Thales Navigation was ultimately purchased by MiTAC ([123]). The author concluded one MiTAC Ashtech DG16 was in use by Team 2004-09, and considers this sensor known.

V.C.10. Team 2004-10

- Team 2004-10 participated in the 2005 GCE as Team 2005-13. See paragraph V.C.38.
- The Team 2004-10 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-10 website was updated prior to the 2005 GCE and reflects the challenge vehicle configuration during the 2005 GCE.
- Team 2004-10 was one of only a few teams to publish their results following the 2004 GCE.
- Team 2004-10 completed the 2004 QID course on the second and last day of the 2004 QID ([84] and [79]).
- Team 2004-10 was selected to participate in the 2004 GCE ([80]).

V.C.10.a. Unknown state sensors

Team 2004-10 stated: “Vehicle state is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), current and voltage sensors.” ([77], p. 4), but reported no additional identifying information. The author was unable to estimate the quantity of state sensors in accordance with paragraph V.B.3.a. because Team 2004-10 reported no information about the intended use of the sensors, and considers these sensors unknown.

V.C.10.b. Riegl LMS-Q140i and unknown SICK LIDAR sensors

Throughout the team technical paper ([77]), Team 2004-10 referred to "LIDAR", "LIDAR scanner", "LIDAR line scanner", "long range LIDAR line scanner", and "short range LIDAR line scanner" as sensors in use by the team, but reported no additional identifying information for either long-range or short-range LIDAR sensors in use by the team.

Team 2004-10 later stated: "A Riegl Q140i scanning laser range finder was selected as the primary sensor..." ([39], p. 13) and "Three SICK LMS laser scanners are used to provide short range supplemental sensing." ([39], p. 14). Team 2004-10 did not report the model number of the SICK LIDAR sensors in use by the team.

The author concluded one Riegl LMS-Q140i was in use by Team 2004-10, and considers this sensor known, and concluded three SICK LIDAR sensors were in use by Team 2004-10, but considers the model number of this sensor unknown.

V.C.10.c. Navtech DS2000

Throughout the team technical paper ([77]), Team 2004-10 referred to "RADAR", "RADAR scanner", and "FMCW RADAR scanner" as sensors in use by the team, but reported no additional identifying information.

Team 2004-10 later stated: "To fill the role of complementary sensor, the NavTech DS2000 Continuous Wave Frequency Modulated (CWFM) radar was selected." ([39], p. 14) and "The RADAR was not integrated with the primary navigation system due to difficulties extracting noise free data." ([39], p. 14). Team 2004-10 did not refer to the RADAR sensor in use by the team in subsequent pages and throughout the section titled "Navigation Software", including Figure 11, which is a block diagram showing the Riegl and SICK LIDAR sensors provide input to the navigation software ([39]).

The author considers this sensor known, but concluded the Navtech DS2000 RADAR was not in use by Team 2004-10 during the 2004 GCE.

V.C.10.d. Unknown SAIC stereo camera pair

Throughout the team technical paper ([77]), Team 2004-10 referred to both a "Stereo video camera pair" and "stereovision camera pair" as sensors in use by the team, but reported no additional identifying information.

Team 2004-10 later stated: "To complement the low density, long range stereo vision system, [the challenge vehicle] incorporates a high speed stereo vision system. The stereo system, provided by SAIC..." ([39], p. 14). Although, unlike the RADAR sensor, Team 2004-10 did not affirmatively state that the stereo camera pair was not integrated with the primary navigation system, Team 2004-10 stated: "After reviewing the logged stereo imagery from race day, it is apparent that the onboard stereo system would have been of little benefit during the early portions of the race.” ([39], p. 39). Team 2004-10 did not refer to the stereo camera pair in use by the team in subsequent pages and throughout the section titled “Navigation Software”, including Figure 11, which is a block diagram showing the Riegl and SICK LIDAR sensors provide input to the navigation software ([39]).

The author considers the quantity and manufacturer of this sensor known, but model number unknown, and concluded the SAIC stereo camera pair was not in use by Team 2004-10 during the 2004 GCE.

V.C.10.e. Unknown other navigation sensors

Team 2004-10 stated: “Vehicle state is reported by … vehicle Pose (roll, pitch, yaw), and vehicle velocity.) ([77], p. 4). The author estimated the quantity of other navigation sensors in accordance with paragraph V.B.5.c., but otherwise considers these sensors unknown.

V.C.10.f. Unknown Applanix sensor

Team 2004-10 stated: “Applanix POS unit is utilized for inertial/GPS/DMI instrumentation.” ([77], p. 5), but reported no additional identifying information. Team 2004-10 later stated: “The Applanix POS-LV provides position estimates...” ([39], p. 14), but did not report the model number of the Applanix POS LV sensor in use by the team.

Applanix currently manufactures several model numbers of the POS LV for land navigation: 200, 220, 420, and 610 ([120]). At least two of these model numbers were available at the time of the 2004 QID and GCE: 220 and 420 ([124]), and the author concluded 320 was an existing model number at the time of the 2004 GCE based on review of manufacturer product literature (See paragraph V.C.8.d.). Applanix later confirmed an Applanix sensor was in use by Team 2004-10 during the 2004 GCE, but reported no additional identifying information ([125]).

The author concluded one Applanix sensor was in use by Team 2004-10, but considers the model number of this sensor unknown.

V.C.11. Team 2004-11

- The Team 2004-11 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-11 website was updated in anticipation of the 2005 NQE, and stated: “we continue to work to finish and perfect the system” ([126]), but reported no additional identifying information for the sensors in use by the team.
- Team 2004-11 did not participate in the 2004 QID or GCE.

V.C.11.a. Unknown tachometer

Team 2004-11 stated: “A tachometer consisting of an induction sensor/counter on the IC engine ignition system provides engine speed data to the engine/transmission microcontroller.” ([127], p. 6), but reported no additional identifying information. The author concluded one tachometer was in use by Team 2004-11, but otherwise considers this sensor unknown.

V.C.11.b. Unknown long-range laser ranger and unknown scanning laser range finder

Team 2004-11 alternately referred to both a “long-range laser ranger” and “scanning laser rangefinder” ([127], p. 4). When referring to a “laser range finder”, Team 2004-11 stated: “This instrument is a standard industrial laser rangefinder...” ([127], p. 5). However, it is unclear to which laser sensor Team 2004-11 was referring as a “laser range finder”, and Team 2004-11 reported no additional identifying information for either sensor.

The author concluded one long-range laser ranger and one scanning laser range finder was in use by Team 2004-11, but otherwise considers these sensors unknown.

V.C.11.c. Unknown Omnivision sensor

Team 2004-11 stated: “...an Omnivision digital image sensor array will also be employed for path identification.” ([127], p. 5), but reported no additional identifying information. Omnivision manufactures several “digital image sensors” ([128]). The author concluded one Omnivision sensor was in use by Team 2004-11, but considers the model number of this sensor unknown.

V.C.11.d. MiTAC A12 and unknown CSI Wireless DGPS receiver

Team 2004-11 stated: “...a Thales A12 GPS receiver, in tandem with a CSI Wireless differential beacon receiver...” ([127], p. 6), but reported no additional identifying information. Through a series of mergers and acquisitions Thales Navigation was ultimately purchased by MiTAC ([123]). The author concluded one MiTAC A12 GPS receiver was in use by Team 2004-11, and considers this sensor known. The author concluded one CSI Wireless DGPS receiver was in use by Team 2004-11, but considers the model number of this sensor unknown.

V.C.11.e. Unknown other navigation sensors

Team 2004-11 stated: “[The challenge vehicle] will derive pitch and roll relative to ground from the scanning laser rangefinder.”, “Ground speed is now derived from an optical interrupter linked to the transmission output shaft.”, and “A solid-state magnetic compass module will be used in conjunction with the odometer...” ([127], p. 6), but reported no additional identifying information for the other navigation sensors in use by the team. The author concluded one of each sensor was in use by Team 2004-11, but otherwise considers these sensors unknown.

V.C.12. Team 2004-12

- The Team 2004-12 website was no longer available.

- Team 2004-12 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), terminated their attempt on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).

- Team 2004-12 was not selected to participate in the 2004 GCE ([80]).

V.C.12.a. Ultra Motion 2-B.125-DC426_12-4-P-/4-300

In response to 2004 SQ 1.a.3 (see Table XXII), Team 2004-12 reported one "Ultramotion 2-B.125-DC426_12-4-P-/4-300 linear actuator" was in use by the team "for each axle" ([129], p. 3). A company named "Ultra Motion" manufactures linear actuators with similar model numbers. The author concluded "Ultramotion" was an error.

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-12 stated linear potentiometers were in use by the team to determine "Wheel Angle for Front and Rear" ([129], p. 5), but reported no additional identifying information. Ultra Motion's online product catalog ([130]) reported an integrated linear potentiometer is denoted by the letter "P" in the model number, above; the same linear actuator without an integrated linear potentiometer is "2-B.125-DC426_12-4-/4-300". The author concluded two Ultra Motion 2-B.125-DC426_12-4-P-/4-300 linear actuators were in use by Team 2004-12 with integrated linear potentiometers, and considers these sensors known.

V.C.12.b. Omron E2E-CR8B1 proximity sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-12 stated two Omron "Omron E2E-CR8BI" sensors were in use by the team as a speedometer and to determine engine speed ([129], p. 5). However, the Omron Corporation "E2E Model Number Legend" ([131]) reported no such model number is possible. The author concluded the model number was "E2E-CR8B1" and that this error was likely to be the result of the similarity between "I" (the capital letter "i") and "1" (the number one) in some sans-serif fonts, and considers these sensors known.

V.C.12.c. Ultrasonic sensors

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-12 stated three short-range ultrasonic distance sensors were in use by the team ([129], p. 4), but reported no additional identifying information. The author concluded three ultrasonic sensors were in use by Team 2004-12, but otherwise considers these sensors unknown.

V.C.12.d. SICK LMS 291-S05

Team 2004-12 stated their "Forward radar distance sensor" was a "SICK Laser Measurement System (LMS) 291-S05" ([129], p. 4). However, the SICK LMS 291-S05 is a LIDAR sensor, not a RADAR sensor. The author concluded this was an error and considers this sensor known.

V.C.13. Team 2004-13

- Team 2004-13 participated in the 2005 GCE as Team 2005-15. See paragraph V.C.39.
- Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE, and many of the technical details of their challenge vehicles were the same.
- The Team 2004-13 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-13 website was no longer available.
- Team 2004-13 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), terminated their attempt on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-13 was selected to participate in the 2004 GCE ([80]).

V.C.13.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-13 stated: "...there will be direct sensing of the state of the vehicle's transmission (reverse, neutral, or forward), the steering angle, the throttle position, and the braking pressure." ([132], p. 4), but reported no additional identifying information. The author estimated the quantity of state sensors in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.13.b. Unknown Hall Effect sensor and unknown absolute encoder

Team 2004-13 variously stated: "Differential odometer. The incremental distance traveled by the vehicle during a steering maneuver will be measured using a Hall effect sensor on the drive shaft..." ([132], p. 4); "For steering, the speed will be obtained from the Hall effect sensor." ([132], p. 5); "The pinion shaft also has attached an absolute encoder in order to determine exact position of the steering." ([132], p. 1); and "Steering rate and angle. This will be measured using an encoder on the steering servo." ([132], p. 5).

Team 2004-13 did not report enough information to determine the quantity of Hall Effect sensors used in the differential odometer, or even if a differential odometer was in use by the team (at least two sensors are required, and they cannot both be attached to the vehicle drive shaft); to determine if a Hall Effect sensor is used to measure vehicle speed in addition to the Hall Effect sensors used in the differential odometer; or to determine the quantity of absolute encoders used in the steering system, one of which is attached to the "pinion shaft" and the other to the "steering servo".

The author concluded no differential odometer was in use by the team, that one Hall Effect sensor was in use to determine the "incremental distance traveled by the vehicle during a steering maneuver" and "speed", and that one "absolute encoder" was in use to determine "steering rate and angle", but otherwise considers these sensors unknown.

V.C.13.c. Unknown compass

Team 2004-13 stated: "A digital compass will provide an absolute orientation clue for maintaining overall correct direction." ([132], p. 5), but reported no additional identifying information. The author concluded one compass was in use by Team 2004-13, but otherwise considers this sensor unknown.

V.C.13.d. Unknown camera

Team 2004-13 stated, in part: "A video camera (pinhole lens, NTSC video, 30 fps) will be ... used..." ([132]], p. 3), but reported no additional identifying information.

Team 2005-15 did not report a video camera was in use by the team.

The author concluded one camera was in use by Team 2004-13, but otherwise considers this sensor unknown.

V.C.13.e. Unknown SICK LIDAR sensors

Teams 2004-13 stated: "*As many as four* LADAR units (SICK LMS) will be used for long-range obstacle detection. In this configuration, two of the units will be used for detecting obstacles within a 180º sector of the horizontal plane directly in front of the vehicle and two units will be mounted vertically so that the laser beam is directed forward and scanned in elevation." ([132], p. 3, *emphasis added*).

Team 2005-15 stated: "The main obstacle sensing is based on SICK LIDAR sensors. Two of these sensors are used to scan horizontally, to detect objects that are in the path to be driven. Two other LIDAR sensors scan vertically, to detect surface continuity and discontinuity (negative obstacles)." ([53], p. 9) and "Five sensors were used to search for obstacles within the corridor: The stereo vision system (SVS) from Seibersdorf Research and four SICK LMS-221 light detection and ranging device (LIDAR) units..." ([133], p. 586).

Although Team 2004-13 stated “as many as four” LIDAR sensors would be used by the team, the author concluded four LIDAR sensors were in use. However, neither Team 2004-13 nor Team 2004-14 reported a model number for the SICK LIDAR sensors in use by the team. The technical capabilities of any of the SICK LMS 2XX LIDAR sensors match the “maximum range”, “angular range”, angular resolution, and “frame update time” reported by Teams 2004-13 and 2004-14 ([74] and [73]).

The author was unable to determine what Teams 2004-13 and 2004-14 were describing by “range resolution”. This may correspond to “Resolution/typ. measurement accuracy” ([73]) or “Resolution/systematic error” ([74]). The resolution of LMS 2XX LIDAR sensors is either “10 mm/± 35 mm” or “10 mm/± 15 mm” ([74] and [73]), with a potential error of -25 to 45 mm and -5 to 25 mm, respectively, or an “error range” of 70 mm (0.07 m) or 30 mm (0.03 m), neither of which correspond to the “range resolution of ~0.3 m” reported by Teams 2004-13 and 2004-14.

The author concluded four SICK LIDAR sensors were in use by Team 2004-13, but considers the model numbers of these sensors unknown.

V.C.13.f. Unknown Epsilon Lambda RADAR

Team 2004-13 stated: “The RADAR system (from Epsilon Lambda) may be used, primarily for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20º with an azimuth angular resolution of 1.8º. It will also have a capability to provide target elevation data over a range of 7.6º with a resolution of 1º.” ([132], p. 3), but reported no additional identifying information.

The Team 2004-21 technical paper contains a specification sheet for the Epsilon Lambda ELSC71-1A as an appendix. The technical capabilities of the Epsilon Lambda ELSC71-1A match the “maximum range”, “range resolution”, “maximum angular range”, and “azimuth angular resolution” reported by Teams 2004-13 and 2004-14 ([74] and [73]).

However, due to the limited availability of manufacturer product literature, the author was unable to determine what other products manufactured by Epsilon Lambda have similar technical capabilities. The author concluded one Epsilon Lambda RADAR was in use by Team 2004-13, but considers the model number of this sensor unknown.

V.C.13.g. Unknown ultrasonic sensors

Team 2004-13 stated: "The ultrasonic range finder will be primarily used for detecting obstacles at short distances on the sides, in front of the vehicle, and to the rear of the vehicle. ... There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one." ([132], p. 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.13.h. Unknown Rockwell Automation photoelectric sensors

Team 2004-13 stated: "The photoelectric sensors (Rockwell Automation types commonly used in industrial automation) may be used. ... The majority of the approximately 24 photoelectric sensors to be used around our vehicle..." ([132], p. 4), but reported no additional identifying information. The author estimated 24 Rockwell Automation photoelectric sensors were in use by Team 2004-13, but considers the model number of these sensors unknown.

V.C.13.i. Unknown accelerometer

Team 2004-13 stated: "An accelerometer capable of sensing movements in the vertical direction will be used to monitor the roughness of the terrain." ([132], p. 5), but reported no additional identifying information. The author concluded one accelerometer was in use by Team 2004-13, but otherwise considers this sensor unknown.

V.C.14. Team 2004-14

- Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE, and many of the technical details of their challenge vehicles were the same.
- The Team 2004-14 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-14 website was no longer available.
- Team 2004-14 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), and completed the 2004 QID course on the third day of the 2004 QID ([85]).
- Team 2004-14 was selected to participate in the 2004 GCE ([80]).

V.C.14.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-14 stated: "...there will be direct sensing of the state of the vehicle's transmission (reverse, neutral, or forward), the steering angle, the throttle position, and the braking pressure." ([134], p. 5), but reported no additional identifying information. The author estimated the quantity of state sensors in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.14.b. Unknown Hall Effect sensor and unknown angular encoder

Team 2004-14 variously stated: "Differential odometer. The incremental distance traveled by the vehicle during a steering maneuver will be measured using a Hall effect sensor on the drive shaft..." ([134], p. 5); "For steering, the speed will be obtained from the Hall effect sensor." ([134], p. 5); and "Steering rate and angle. This will be measured using an angular encoder on the steering column." ([134], p. 5).

Team 2004-14 did not report enough information to determine the quantity of Hall Effect sensors used in the differential odometer, or even if a differential odometer was in use by the team (at least two sensors are required, and they cannot both be attached to the vehicle drive shaft); or to determine if a Hall Effect sensor is used to measure vehicle speed in addition to the Hall Effect sensors used in the differential odometer.

The author concluded no differential odometer was in use by the team, that one Hall Effect sensor was in use to determine the "incremental distance traveled by the vehicle during a steering maneuver" and "speed", and that one "angular encoder" was in use to determine "steering rate and angle", but otherwise considers these sensors unknown.

V.C.14.c. Unknown magnetometer

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." ([134], p. 6), but reported no additional identifying information. The author concluded one magnetometer was in use by Team 2004-14, but otherwise considers this sensor unknown.

V.C.14.d. Unknown cameras

Team 2004-14 stated, in part: "A set of video cameras (pinhole lens, NTSC video, 30 fps) will be ... used..." ([134], p. 3), but reported no additional identifying information. The author considers these sensors unknown.

V.C.14.e. Unknown SICK LIDAR sensors

Team 2004-14 stated: "*As many as four* LADAR units (SICK LMS) will be used for long-range obstacle detection. In this configuration, one of the units will be used for detecting obstacles within a 100º sector of the horizontal plane directly in front of the vehicle and *either one or two units* will be used for detecting obstacles in the horizontal plane of the left and right forward quadrants to provide obstacle detection when maneuvering to the left or right. One of the LADAR systems will be mounted so that the laser beam is directed forward and scanned in elevation." ([134], pp. 3 - 4, *emphasis added*).

Although Team 2004-14 reported that either three or four LIDAR sensors were in use by the team, the author considers it likely that Team 2004-14 used the same quantity of LIDAR sensors as Team 2004-13, and concluded four SICK LIDAR sensors were in use by Team 2004-14.

Neither Team 2004-13 nor Team 2004-14 reported a model number for the SICK LIDAR sensors in use by the team. See paragraph V.C.13.e. The author considers the model number of these sensors unknown.

V.C.14.f. Unknown Epsilon Lambda RADAR

Team 2004-14 stated: "The RADAR system (from Epsilon Lambda) will be primarily used for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20º with an azimuth angular resolution of 1.8º. It will also have a capability to provide target elevation data over a range of 7.6º with a resolution of 1º." ([134], p. 4), but reported no additional identifying information.

Neither Team 2004-13 nor Team 2004-14 reported the model number for the Epsilon Lambda RADAR in use by the team. See paragraph V.C.13.f. The author concluded one Epsilon Lambda RADAR was in use by Team 2004-14, but considers the model number of this sensor unknown.

V.C.14.g. Unknown ultrasonic sensors

Team 2004-14 stated: "The ultrasonic range finder will be primarily used for detecting obstacles at short distances on the sides, in front of the vehicle, and to the rear of the vehicle. ... There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one." ([134], p. 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.14.h. Unknown Rockwell Automation photoelectric sensors

Team 2004-14 stated: "The photoelectric sensors will be Rockwell Automation types commonly used in industrial automation... ... The majority of the approximately 24 photoelectric sensors to be used around our vehicle..." ([134], p. 4), but reported no additional identifying information. The author estimated 24 Rockwell Automation photoelectric sensors were in use by Team 2004-14, but considers the model number of these sensors unknown.

V.C.14.i. Unknown tactile sensors

Team 2004-14 stated: “Flexible bumper tactile sensors will be able to detect contact with objects at ≤8 inches around the vehicle.” ([134], p. 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.14.j. Unknown accelerometer

Team 2004-14 stated: “An accelerometer capable of sensing movements in the vertical direction will be used to monitor the roughness of the terrain.” ([134], p. 5), but reported no additional identifying information. The author concluded one accelerometer was in use by Team 2004-14, but otherwise considers this sensor unknown.

V.C.14.k. Rockwell Collins GNP-10

Team 2004-14 alternately stated: “The primary navigation will be through a Navcom Starfire SF-2050G DGPS receiver. It will be hooked up to a IMU (Rockwell Collins, GMC-10, alternatively a Systron Donner C-Migit III).” ([134], p. 5) and “The vehicle determines its geo-location using El-Op's GemiNav INS/DGPS system that uses the Northrop Grumman LN-200 IMU and Trimble Pathfinder DGPS unit.” ([134], p. 6).

Rockwell Collins reported no IMU with the model number “GMC-10” existed (see Figure 36). An IMU with model number “GNP-10” exists (see Figure 37), and it is to this model number that Team 2004-13 referred ([132], p. 4). Team 2004-13 did not refer to either a Systron Donner C-Migit III IMU, El-Op's GemiNav INS/DGPS system, or Northrop Grumman LN-200 IMU, and neither Team 2004-13 nor Team 2004-14 later stated these sensors were in use during the 2004 GCE ([135]).

The author concluded neither a Systron Donner C-Migit III IMU, El-Op GemiNav INS/DGPS system, nor Northrop Grumman LN-200 IMU were in use by Team 2004-14, that “GMC-10” was an error, and that the IMU in use by Team 2004-14 was identical to the IMU in use by Team 2004-13. As a result, the author considers this sensor known.

V.C.15. Team 2004-15

- The Team 2004-15 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The Team 2004-15 website reported no additional identifying information for the sensors in use by the team.

- Via an “An Important Message from the Team Leader”, dated March 1, 2004, Team 2004-15 stated: “Although the team has worked diligently and sacrificed much in our effort to have [the challenge vehicle] ready for the [2004 GCE], 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]).

- Team 2004-15 did not participate in the 2004 QID or GCE.

V.C.15.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated: "Vehicle sensors are … steering position, brake position, throttle position, RPM, low oil pressure, transmission shifter position, transfer case shifter position, air conditioning information which is used for temperature management in the water tight electronics enclosure..." ([137], p. 3), but reported no additional identifying information. The author estimated the quantities of the state sensors in use by Team 2004-15 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.15.b. Polaroid 6500 SONAR sensors

Team 2004-15 stated: "Active 50KHz ultrasonic sonar with a sensing horizon of 10 meters will be used for near obstacle detection to the front, rear and sides of the vehicle." ([137], p. 3). Via "Attachment A" ([137], p. 7), Team 2004-15 identified one fixed mount point each for the left side, front, and right side SONAR sensors in use by the team, and two mount points for the rear SONAR sensors. In response to 2004 SQ 3.e.1 (see Table XXII), Team 2004-15 stated a "POLAROID 6500 Ultrasonic Ranger, 50 KHz" was in use by the team ([137], p. 6). The author concluded five Polaroid 6500 SONAR sensors were in use by Team 2004-15, and considers these sensors known.

V.C.15.c. Unknown tactile sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated "front and rear tactile sensors" were in use by the team ([137], p. 3), but reported no additional identifying information. The author considers these sensors unknown.

V.C.15.d. Unknown wheel encoders

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated "encoders on all 4 wheels" were in use by the team ([137], p. 3), and in response to questions 1.g.1 and 1.g.2, Team 2004-15 stated: "Wheel encoders on the vehicle are used to compute distance traveled." ([137], p. 4), but reported no additional identifying information. The author concluded four wheel encoders were in use by Team 2004-15, but otherwise considers these sensors unknown.

V.C.15.e. Unknown accelerometer

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated a "3-axis accelerometer" was in use by the team ([137], p. 3), but reported no additional identifying information. The author concluded one accelerometer was in use by Team 2004-15, but otherwise considers this sensor unknown.

V.C.16. Team 2004-16

- Team 2004-16 participated in the 2005 GCE as Team 2005-17. See paragraph V.C.41.
- The Team 2004-16 website was updated prior to the 2005 GCE, but reported limited additional identifying information for the sensors in use by the team.
- Team 2004-16 aborted its run due to a minor malfunction by a course transmitter on the first day of the 2004 QID ([78]), and partially completed the 2004 QID course on the third and last day of the 2004 QID ([85] and [79]).
- Team 2004-16 was selected to participate in the 2004 GCE ([80]).

V.C.16.a. Unknown state sensors

Team 2004-16 reported no detailed state sensor information in response to questions specifically requesting state sensor information. In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-16 stated: "Vehicle state sensed by interface with engine electronics (e.g., stalled engine)." ([138], p. 4); and in response to 2004 SQ 1.f.2 (see Table XXII), Team 2004-16 stated: "Data is monitored using custom software via a GPS." ([138], p. 4).

V.C.16.b. Unknown compass

Throughout the team technical paper ([138]), Team 2004-16 variously referred to a "compass", "digital compass", and "electronic compass", but reported no additional identifying information. The author concluded one compass was in use by Team 2004-16, but otherwise considers this sensor unknown.

V.C.16.c. Unknown cameras

Team 2004-16 stated: "Passive cameras, 2 fixed front wide-angle IR sensitive CCD cameras for visual acquisition of terrain, obstacles, other vehicles (1-90m)..." ([138], p. 4), but reported no additional identifying information. The challenge vehicle description on the Team 2004-16 website did not report "cameras" of any kind were in use by the team ([139]). The author concluded two cameras were in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.16.d. Unknown RADARs

In addition to a number of generic references to the use of RADAR for obstacle detection, Team 2004-16 stated: “The radars ... use beams that will be reflected back from the road.” ([138], p. 7) and “Radar devices operate at 24.725 GHz with a maximum power output of less than 5mW.” ([138], p. 8), but reported no additional identifying information.

Team 2005-17 stated: “The radar and sonar sensors are removed.” ([140], p. 2), but reported no additional identifying information.

The author concluded more than one RADAR was in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.16.e. Unknown SONAR sensors

Team 2004-16 stated: “The system classifies objects acquired through sonar and radar using filtering techniques applicable to sonar and radar target identification.” ([138], p. 3), but reported no additional identifying information.

Team 2005-17 stated: “The radar and sonar sensors are removed.” ([140], p. 2), but reported no additional identifying information.

The author concluded SONAR sensors were in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.16.f. Unknown SICK LIDAR sensors

Team 2004-16 stated: “...laser range finders for distance determination between own vehicle and obstacle/other vehicles (1-100m).” ([138], p. 4), but reported no additional identifying information.

Team 2004-16 reported “Two scanning laser systems” were in use by the team, but reported no additional identifying information ([139]).

Team 2005-17 stated: “The single (functional) SICK LMS 221 is augmented by four SICK LMS 291s.” ([140], p. 2).

In the absence of an affirmative statement by Team 2005-17 that the “single (functional) SICK LMS 221” LIDAR sensor referred to via the team technical paper ([140]) was one of the “laser range finders” in use by Team 2004-16 during the 2004 QID and GCE, the author concluded two SICK LIDAR sensors were in use by Team 2004-16, but considers the model number of these sensors unknown.

V.C.16.g. Unknown C&C Technologies C-Nav and unknown INS

Team 2004-16 stated: "Software integrates GPS/inertial/compass/pitch/yaw data for navigation. Sensor data are combined (inertial and GPS using Kalman filtering)..." ([138], p. 3), but reported no additional identifying information.

Team 2004-16 reported the "C-Nav differential GPS" and "an Oxford inertial navigation sensor" were in use by the team ([139]). The C-Nav DGPS receiver is a product of C&C Technologies. C&C Technologies manufactured several model numbers of the C-Nav at the time of the 2005 GCE ([141]). The author concluded one C&C Technologies C-Nav DGPS receiver was in use by Team 2004-16, but considers the model number of this sensor unknown.

Team 2005-17 stated: "The POS/MV INS from Applanix has been replaced by RT3102 from Oxford Technologies." ([140], p. 2). As a result, the author concluded the Oxford RT3102 was not in use by the team during the 2004 QID and GCE. In the absence of an affirmative statement that the Applanix POS MV was in use by the team during the 2004 QID and GCE, the author concluded one INS was in use, but otherwise considers this sensor unknown.

V.C.16.h. Unknown solar sensors

Team 2004-16 stated: "Navigation sensors include ... solar sensors..." ([138], p. 10), but reported no additional identifying information. The author concluded solar sensors were in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.17. Team 2004-17

- Team 2004-17 participated in the 2005 GCE as Team 2005-18. See paragraph V.C.42.
- The Team 2004-17 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-17 website was updated prior to the 2007 Urban Challenge, but reported no additional identifying information for the sensors in use by the team.
- Team 2004-17 partially completed the 2004 QID course before stopping to make mechanical adjustments on the first day of the 2004 QID ([78]), and completed the 2004 QID course on the third and last day of the 2004 QID ([85] and [79]).
- Team 2004-17 was selected to participate in the 2004 GCE ([80]).

V.C.17.a. OBD-II

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-17 stated: “Vehicle diagnostic state will be provided by the car’s built-in On-Board Diagnostic system, which will provide, among other data, engine temperature, engine RPM, and present gear.” ([142], p. 8). In response to 2004 SQ 2.a (see Table XXII), Team 2004-17 stated: “We found the data from OBD-II to be less than reliable. Further testing is required to determine if any of the OBD-II data will be useful.” ([142], p. 11). As a result, it is unclear if OBD-II data was in use by Team 2004-17. However, in the absence of an affirmative statement by the team that OBD-II data was not in use by the team during the 2004 GCE, the author concluded the OBD-II system was in use as a state sensor, and considers this sensor known.

V.C.17.b. Indigo Omega

Team 2004-17 stated: “The end result of the test was the decision to purchase [an Indigo Omega] long-wave infrared camera.” ([142], p. 12). However, the table of environmental sensors reported by the team technical paper ([142], p. 7) does not list this sensor as one in use by the team. The author concluded the Indigo Omega was not in use by Team 2004-17.

V.C.17.c. Point Grey Dragonfly cameras

Team 2004-17 stated Point Grey Dragonfly cameras were in use by the team as a “long-range forward-looking stereo camera pair”, “short-range forward-looking stereo camera pair”, and “road following camera” ([142], p. 7).

Point Grey has product lines named “Bumblebee”, “Dragonfly”, “Flea”, etc. ([108]). Each product line has multiple model numbers. The current model number for the Dragonfly product line is “Dragonfly 2” ([143]). The Dragonfly 2 was introduced January 20, 2005 ([144]). Point Grey did not manufacture a Dragonfly or Dragonfly 2 stereo camera pair ([145], [143], and [146]).

The author concluded each “stereo camera pair” was comprised of two Dragonfly cameras, that the total quantity of Dragonfly cameras in use by the team was five, and that “Dragonfly” was the model number at the time of the 2004 QID and GCE, and considers these sensors known.

V.C.18. Team 2004-18

- Team 2004-18 participated in the 2005 GCE as Team 2005-20. See paragraph V.C.44.
- The Team 2004-18 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The hyperlink hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) to the Team 2004-18 website is actually a hyperlink to the ENSCO, Inc. corporate website, which reported no additional identifying information for the sensors in use by the team.

- The team technical paper ([48]) referred to missing Figures “1”, “2”, “3”, and “5”, but did not refer to confidential or proprietary appendixes (see paragraph V.E.2.f.).

- Team 2004-18 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), nearly completed the 2004 QID course on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).

- Team 2004-18 was selected to participate in the 2004 GCE ([80]).

V.C.18.a. Unknown state sensors

Team 2004-18 stated: “There are also sensors to detect if the engine is running, if brakes are applied, if acceleration is applied, and the position of the steering motor.” ([48], p. 6), but reported no additional identifying information. The author estimated the quantity of these sensors in accordance with paragraph V.B.3.a., but otherwise considers them unknown.

Team 2004-18 also stated: “There are also temperature sensors to monitor engine and other critical components.” ([48], p. 6), but reported no additional identifying information. The author considers these sensors unknown.

V.C.18.b. Unknown compass

Team 2004-18 stated a “magnetic compass” was in use by the team, but reported no additional identifying information ([48], pp. 6 - 7). The author concluded one magnetic compass was in use by Team 2004-18, but otherwise considers this sensor unknown.

V.C.18.c. Unknown ISI INS

Team 2004-18 stated: “The vehicle has an inertial navigation system (INS-Inertial Science Inc. RRS75). This device has 3 accelerometers and 3 rate gyros that will provide the control system with information for 6 degrees-of-freedom of the vehicle state. This is integrated into the dead reckoning and the vehicle navigation control system. The purpose of the INS is to determine vehicle stability as well as to assist with determining vehicle position.” ([48], p. 6).

Concerning the RRS75, ISI stated: “The RRS (Resonator Rate Sensor) is a new technology sensor that has been developed by Inertial Science, Inc. (ISI) and Sandia

National Laboratory, for angular rate measurement applications." ([147]). ISI also stated: "ISI has designed a complete Inertial Navigation System (ISIS-IMU) utilizing the RRS for its rate sensors. This system allows GPS integration." ([147]).

The ISIS-IMU more closely matches the description of the "inertial navigation system" referred to by Team 2004-18: "ISIS-IMU is a six-degree of freedom inertial mesurement [*sic*] unit designed for commercial use." and "It consists of three RRS75 (solid state rate sensors) and three solid state accelerometers." ([148]). In addition, ISIS-IMU integrates with GPS.

The author concluded Team 2004-18 did not report sufficient technical detail to determine to which "inertial navigation system" Team 2004-18 referred via the team technical paper ([48]), concluded one ISI INS was in use by the team, and considers the model number of this sensor unknown.

V.C.18.d. Unknown RADAR

Team 2004-18 stated: "The primary sensors are one LIDAR systems [*sic*], 3 doppler radars, and a stereo camera system." ([48], p. 5); "The Doppler radar sensors are planned to be DRS 1000 units from GMH engineering." ([48], p. 12); and "Modifications of the tested system will be done to meet the final configuration presented in this paper." ([48], p. 8). The author concluded three Doppler RADAR sensors were in use by the team, but does not consider the manufacturer and model number known in the absence of an affirmative statement by Team 2004-18 that GMH Engineering DRS 1000 RADAR was in use, because alternate RADAR sensors were in use by other teams which participated in the 2004 GCE with similar characteristics, e.g., PRECO PreView.

V.C.18.e. NovAtel ProPak-LBplus

Team 2004-18 stated: "Anovatel Pro-Pack LB will be used for the challenge vehicle." ([48], p. 6). NovAtel is the manufacturer name. The author concluded this was a typographical error and considers this sensor known[21].

V.C.18.f. SICK LMS 220-30106

Team 2004-18 stated: "The primary sensors are one LIDAR systems [*sic*], 3 doppler radars, and a stereo camera system." ([48], p. 5) and "One SICK model LMS 220-30106 scanning LIDAR will be fitted to the front of the vehicle. Each [*sic*] will scan a 180 deg arc with some overlap at the extended centerline of the vehicle. The lasers [*sic*] maximum range is approximately 150m..." ([48], p. 11).

Team 2005-20 stated: "Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems." ([56], p. 2). However, Team 2005-20 reported no additional identifying information for the LIDAR in use by the team.

Through their repeated use of the word "one" to describe "LIDAR systems", and use of the plural "lasers" and word "each", Team 2004-18 alternately stated that both one and more than one SICK LMS 220-30106 were in use by the team. The author concluded this was an error, that one SICK LMS 220-30106 was in use by Team 2004-18, and considers this sensor known.

V.C.18.g. Unknown stereo camera pair

Team 2004-18 stated: "The primary sensors are one LIDAR systems [*sic*], 3 doppler radars, and a stereo camera system." ([48], p. 5) and "The Team will purchase and use an implementation of SRI's Small Vision System (SVS) software that comes standard with certain brands of stereo vision hardware." ([48], p. 5), but reported no additional identifying information for the stereo camera system in use by the team.

Team 2005-20 stated: "Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems." ([56], p. 2). However, Team 2005-20 reported no additional identifying information for the stereo camera pair in use by the team.

The author concluded one stereo camera pair was in use by Team 2004-18, but otherwise considers this sensor unknown.

V.C.19. Team 2004-19

- The Team 2004-19 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-19 website was no longer available.
- The team technical paper ([151]) referred to a missing figure "4", but did not refer to confidential or proprietary appendixes (see paragraph V.E.2.f.).
- Team 2004-19 passed on their turn the second day of the 2004 QID ([84]), and terminated within the starting chute area the last day of the 2004 QID ([79]).
- Team 2004-19 was not selected to participate in the 2004 GCE ([80]).

V.C.19.a. Unknown stereo camera pair

Team 2004-19 stated: "The system uses ... a stereo vision system." ([151], p. 2). Via their response to 2004 SQ 2.a.1 (see Table XXII), Team 2004-19 stated: "We are still working on our stereo vision system, and have not yet interfaced it with the vehicles [*sic*] computing system." ([151], p. 4).

The author concluded one stereo camera pair was in use by Team 2004-19, but otherwise considers this sensor unknown.

V.C.19.b. Unknown ultrasonic sensors

Team 2004-19 stated: “The system uses three ultrasonic rangefinders...” ([151], p. 2), but reported no additional identifying information. The author concluded three ultrasonic sensors were in use by Team 2004-19, but otherwise considers these sensors unknown.

V.C.19.c. Unknown Electro Switch OEs

Team 2004-19 stated: “The DRS is comprised of a Precision Navigation Vector-2X digital compass module integrated with two Oak Grigsby 900 Series optical encoders.” ([151], p. 3). Oak Grigsby was acquired by Electro Switch ([152]). Electro Switch reported “900 Series” is not a complete model number ([152]). The author concluded two Electro Switch OEs were in use by Team 2004-19, but considers the model number of these sensors unknown.

V.C.19.d. PNI Vector 2X

Team 2004-19 stated: “The DRS is comprised of a Precision Navigation Vector-2X digital compass module integrated with two Oak Grigsby 900 Series optical encoders.” ([151], p. 3). Precision Navigation, Inc. became PNI Sensor Corp. in 2000 ([154]). The author concluded PNI was the manufacturer and considers this sensor known.

V.C.20. Team 2004-20

- The Team 2004-20 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- Team 2004-20 maintained an extensive online repository, which is accessible from the Internet but variously marked “Members Only (now public)” and “For participants only. Not for public distribution.”, and which was a rich source of background information for the 2004 and 2005 GCE.
- Team 2004-20 did not participate in the 2004 QID or GCE.

V.C.20.a. Unknown state sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-20 stated: “Engine RPM and driveshaft RPM are monitored, along with some voltages and temperatures.” ([107], p. 6), but reported no additional identifying information. The author estimated the quantity of the engine RPM and driveshaft RPM sensors in use by

Team 2004-20 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.20.b. Eaton EVT-300

Team 2004-20 stated: “An Eaton VORAD anti-collision radar system is fitted to detect collisions with other vehicles and large obstacles. … The radar unit is a standard Eaton VORAD unit, the widely used truck anti-collision radar, interfaced to computers using an Eaton VBOX.” ([107], p. 5), but reported no additional identifying information.

The repository contains several documents which identify the specific model number of the Eaton RADAR in use by Team 2004-20 as “EVT-300”. The author considers this sensor known.

V.C.20.c. Unknown water sensors

Team 2004-20 stated: “Water sensors at two heights are provided to detect when the vehicle has entered water.” ([107], p. 5), but reported no additional identifying information. The author considers these sensors unknown.

V.C.20.d. Unknown ultrasonic sensors

Team 2004-20 stated: “The usual ring of ultrasonic sonars is provided, with overlapping sensing fields surrounding the vehicle.” and “In addition, there are narrow-angle sonars pointing down ahead of each leading wheel and behind each trailing wheel.” ([107], p. 5), but reported no additional identifying information. The author considers these sensors unknown.

V.C.20.e. Unknown Crossbow INS

Team 2004-20 stated: “We are currently planning to use a ... Crossbow AHRS inertial system.” ([107], p. 7), but reported no additional identifying information. Crossbow manufactured several models of “AHRS inertial system” ([96]). The author concluded one Crossbow INS was in use by Team 2004-20, but considers the model number of this sensor unknown.

V.C.20.f. Unknown DICKEY-john RADAR

Team 2004-20 reported one “Dickey-John doppler radar speedometer” was in use by the team ([107], pp. 6, 13), but reported no additional identifying information. The author concluded one DICKEY-john RADAR was in use by Team 2004-20, but considers the model number of this sensor unknown.

V.C.20.g. Unknown compass

Team 2004-20 stated one “magnetic compass” was in use by the team ([107], pp. 6 - 7), but reported no additional identifying information. The author concluded one compass was in use by Team 2004-20, but otherwise considers this sensor unknown.

V.C.21. Team 2004-21

- The hyperlink hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) to the Team 2004-21 website redirects to another domain, which reported no additional identifying information for the sensors in use by Team 2004-21.
- Team 2004-21 passed on their turn on the first day of the 2004 QID ([78]), terminated their attempt on the third day of the 2004 QID ([85]), and officially withdrew on the last day of the 2004 QID ([79]).
- Team 2004-21 was not selected to participate in the 2004 GCE ([80]).

V.C.21.a. Unknown state sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-21 stated: “Fuel, temperature, electrical output, etc.” ([155], p. 6), but reported no additional identifying information. The author estimated the quantity of fuel sensors in use by Team 2004-21 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.21.b. Epsilon Lambda ELSC71-1A

In response to 2004 GCE SQ 1.e.1 (see Table XXII), Team 2004-21 stated: “We will use a Radar system for long range sensing...” ([155], p. 6), but reported no additional identifying information. The team technical paper contains a specification sheet for the Epsilon Lambda ELSC71-1A as an appendix. The author considers this sensor known.

V.C.21.c. SensComp Developer's Kit

In response to 2004 GCE SQ 1.e.1 (see Table XXII), Team 2004-21 stated: “We will use … sonar for short range.” ([155], p. 6). The team technical paper contains a specification sheet for a “Developer's Kit” as an appendix, but reported no additional identifying information. The author concluded SensComp was the manufacturer of the Developer's Kit based on an Internet search using the key words “+'600 series' +'environmental transducer' +7000 +9000” as the search string. As confirmation, the picture embedded in the specification sheet included with the team technical paper ([155]) matches the picture from manufacturer product literature ([156]). The author considers this sensor known.

V.C.21.d. Unknown IR sensors

In response to 2004 GCE SQ 2.a (see Table XXII), Team 2004-21 stated: "The key components that have been tested so far include ... the various IR and Sonar sensors." ([155], p. 9), but reported no additional identifying information. However, Team 2004-21 did not refer to IR sensors in response to 2004 SQ 1.e.i (see Table XXII). The author concluded IR sensors were not in use by Team 2004-21 during the 2004 QID.

V.C.22. Team 2004-22

- The Team 2004-22 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- No hyperlink to the Team 2004-22 website was hosted by DARPA via the Archived Grand Challenge 2004 website ([17]).
- Team 2004-22 did not participate in the 2004 QID or GCE.

V.C.22.a. Unknown SpaceAge Control string potentiometers

In response to 2004 GCE SQ 1.c.2 (see Table XXII), Team 2004-22 stated: "Shock monitoring System (SMS)—each shock is equipped with a string pot to determine the actual position of the shock (compressed or uncompressed)." ([157], p. 3) and "The shock suspension uses SpaceAge Controls, [*sic*] string pots..." ([157], p. 4), but did not report the model number of the string potentiometers in use by the team. The author estimated four SpaceAge Control string potentiometers were in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.b. Unknown temperature sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: "Temperature sensors – used to monitor engine, oil and outside temperatures." ([157], p. 5), but reported no additional identifying information. The author concluded three temperature sensors were in use by Team 2004-22, but otherwise considers these sensors unknown.

V.C.22.c. Team 2004-22 Video System

In response to 2004 SQ 1.b (see Table XXII), Team 2004-22 stated: "Video Processing—See Proprietary Annex" ([157], p. 3). Although Team 2004-22 referred to a "video system" throughout the team technical paper ([157]), including their response to 2004 SQ 1.e.1 (see Table XXII), 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.

The author considers the proprietary video system in use by Team 2004-22 known, but concluded the cost of this sensor cannot be independently determined.

V.C.22.d. Unknown Microstrain gyroscope

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: “3-axis gyro (Microstrain) – used to determine heading of the vehicle, acceleration in any axis and the Eulers / Quaterion [*sic*] matrices to determine the 6-degrees of freedom equations[.]” ([157], p. 5), but reported no additional identifying information. The author concluded one Microstrain 3-axis gyroscope was in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.e. Unknown gyroscope

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: “1-axis gyro – specifically used for the GPS for heading sensing in odometry mode.” ([157], p. 5), but reported no additional identifying information. The author concluded one 1-axis gyroscope was in use by Team 2004-22, but otherwise considers this sensor unknown.

V.C.22.f. Unknown Honeywell pressure transducer

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: “Altitude sensor (Honeywell, SSEC) – highly accurate pressure transducer is used to measure altitude of the vehicle.” ([157], p. 5), but reported no additional identifying information. The author concluded one Honeywell pressure transducer was in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.g. Unknown u-blox GPS receiver

Team 2004-22 stated: “u-Blox GPS, with Wide Area Augmentation System (WAAS), is the secondary means for updating the vehicles position during the race.” ([157], p. 2) and “the u-Blox GPS unit has a self-calibrating sensor feed for odometry. Hall-State proximity sensors are attached to each of the front wheels and two to the rear drive shaft. The GPS requires two more feeds for DR mode; a single-axis gyro and a logic high/low for forward or reverse motion. The Kalman filter on the GPS is self-calibrating.” ([157], p. 3), but reported no additional identifying information.

U-blox manufactured multiple product families, e.g., “GPS modules”, “GPS cards”, and “GPS chips”, each of which has multiple model numbers ([158]), and that at least three current GPS modules offer an integrated Kalman filter: LEA-4R, TIM-4R, and AEK-4R. The author considers it likely that multiple products with the capabilities reported by Team 2004-22 were available at the time of the 2004 QID, and concluded one u-blox GPS receiver was in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.h. Unknown Hall Effect sensors

Team 2004-22 stated: “Hall-State proximity sensors are attached to each of the front wheels and two to the rear drive shaft.” ([157], p. 3). The author concluded four Hall Effect sensors were in use by Team 2004-22, but otherwise considers these sensors unknown.

V.C.23. Team 2004-23

- Team 2004-23 participated in the 2005 GCE as Team 2005-21. See paragraph V.C.45.
- The hyperlink hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) to the Team 2004-23 website was actually a hyperlink to the Oshkosh Defense corporate website. This website hosted a hyperlink to the Team 2004-23 website, which was updated prior to the 2005 GCE, and which reported no additional identifying information for the sensors in use by Team 2004-23.
- Team 2004-23 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), nearly completed the 2004 QID course on the third day of the 2004 QID ([85]), and completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-23 was selected to participate in the 2004 GCE ([80]).

V.C.23.a. Unknown state sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-23 stated: “We will also have access to vehicle and actuator sensors to determine throttle, brakes, and engine condition.” ([159], p. 9), but reported no additional identifying information. The author estimated the quantity of state sensors in use by Team 2004-23 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.23.b. Unknown SICK LIDAR sensors

Team 2004-23 stated: “Four SICK LADARs (Model: LMS 221) are to be used. These are 2-D laser rangefinders (active sensors) with 180 degree scanning spectrum and have maximum scanning distance of 80 meters[.] The actual range, of course, depends on the reflectivity of the target, but our experience to date indicates that 40 meters is a reasonable minimum operational range.” ([159], p. 8), but did not report the model numbers for the four SICK LIDAR sensors in use by the team.

Team 2005-21 used a combination of SICK LMS 291 and IBEO ALASCA LIDAR sensors ([160]).

The author concluded four SICK LIDAR sensors were in use by Team 2004-23, but considers the model number of these sensors unknown.

V.C.23.c. Unknown Eaton RADARs

Team 2004-23 stated: "2 Eaton-Vorad radars are mounted (front and rear) for providing 150 m range target tracking." ([159], p. 9), but reported no additional identifying information.

Team 2005-21 did not refer to RADAR in use by the team ([160] and [57]).

The author concluded two Eaton RADARs were in use by Team 2004-23, but considers the model number of these sensors unknown.

V.C.23.d. Unknown Massa ultrasonic sensors

Team 2004-23 stated: "12 ultrasonic sensors (Massa—8in to 14 ft) are mounted around the vehicle for short range sensing." ([159], p. 9), but reported no additional identifying information. Team 2005-21 did not refer to ultrasonic sensors in use by the team ([160] and [57]). The author concluded 12 Massa ultrasonic sensors were in use by Team 2004-23, but considers the model number of these sensors unknown.

V.C.23.e. Unknown cameras

Team 2004-23 stated: "The vision system consists of 6 CCD digital color cameras. Two pairs are used to provide stereovision information (both forward and rear looking). The two single cameras will sense the terrain in front and behind the truck and provide free-space estimation and path/road estimation." ([159], p. 8), but reported no additional identifying information.

Team 2005-21 stated: "The vision system is comprised of a forward-looking system and a backward looking one. Both systems share the same technology and processing: color cameras and stereoscopic vision." ([160], p. 10); "The forward-looking system consists of three identical cameras mounted on a rigid bar on top of the hood." ([160], p. 10); and "Pairs of stereo images are used for both obstacle detection and path detection." ([160], p. 11). Team 2005-21 did not report additional identifying information for the cameras in use by the team.

The author concluded six CCD digital color cameras were in use by Team 2004-23, but otherwise considers these sensors unknown.

V.C.23.f. Unknown IMU

Team 2004-23 stated: "One inertial measurement unit (IMU) will measure the total accelerations and angular velocity of the vehicle." ([159], p. 9) and "With options 1 and 2, the IMU will be either Honeywell HG1700 or the Litton LN200. Option 3 provides an integrated IMU. A magnetic compass and dead-reckoning information will also be included in the navigation solution. Our current plan is to implement Option 2 as soon as funding is available." ([159], p. 10).

Team 2004-23 did not refer to "options" again throughout the team technical paper ([159]). The author considers it likely this paragraph was copied-and-pasted from another document, such as a proposal, or was an artifact of the PDF conversion process.

Team 2005-21 stated: "Two Oxford Technical Solutions (OXTS) RT3100s supply GPS position information to the VMS system." ([160], p. 8) and "Two Oxford Technical Solutions RT3100's ... supply GPS position information to the iVMS system." ([57], p. 700).

The author concluded one IMU was in use by Team 2004-23, but otherwise considers this sensor unknown.

V.C.23.g. <u>Unknown wheel speed sensors</u>

Team 2004-23 stated: "Individual wheel speed is available off the J1939 bus." ([159], p. 9), but reported no additional identifying information. The author concluded six wheel speed sensors were in use by Team 2004-23, but otherwise considers these sensors unknown.

V.C.24. Team 2004-24

- No hyperlink to the Team 2004-24 website was hosted by DARPA via the Archived Grand Challenge 2004 website ([17]).
- Team 2004-24 partially completed the 2004 QID course on the second and third day of the 2004 QID ([84] and [85]).
- Team 2004-24 was selected to participate in the 2004 GCE ([80]).

V.C.24.a. <u>Unknown pressure sensors</u>

Team 2004-24 stated: "There are two pressure sensors per suspension cylinder and steering cylinder set (one on each side of the piston), two for the brake actuators and one for each storage tanks [*sic*]. There are a total of 19 sensors." ([161], p. 5), but reported no additional identifying information. The author concluded 19 pressure sensors were in use by Team 2004-24, but otherwise considers these sensors unknown.

V.C.24.b. <u>Unknown power system sensors</u>

Team 2004-24 stated: "The power system controller monitors the state of charge of the batteries through voltage and current sensors. The state of the generators is monitored through voltage sensors, speed sensors and water temperature sensors." ([161],

p. 6), but reported no additional identifying information. The author estimated the quantity of power system sensors in use by Team 2004-24 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.24.c. Unknown cameras

Team 2004-24 alternately referred to a "road ID camera" and "road ID cameras" or "boundary ID camera" and "boundary ID cameras", and "binocular vision", and stated: "The Boundary ID cameras are low resolution video sensors primarily used to identify artificial boundaries installed by the DAPRA Grand Challenge staff."; "The road ID cameras use texture ID algorithms to identify roads/trails along with associated confidence levels."; and "The matched set of machine vision cameras are the first of three sensors used to construct a near real time solid model for low to moderate speed navigation." ([161], p. 5).

Figure 2 ("Processing System Layout") of the team technical paper ([161], p. 12) reported that there are two "Road Following" cameras and two "Vision Cameras", but no "boundary ID" cameras. Therefore, the author estimated two road ID cameras were in use by Team 2004-24; concluded the quantity of boundary ID cameras is unknown; and concluded one matched set of machine vision cameras were in use by the team as a stereo camera pair. The author considers the manufacturers and model numbers of the cameras in use by Team 2004-24 unknown.

V.C.24.d. Unknown LIDAR sensor

Team 2004-24 stated: "The Lidar sensor is the final sensor used for solid model construction. It is the primary obstacle avoidance sensor." ([161], p. 5), but reported no additional identifying information. The author concluded one LIDAR sensor was in use by Team 2004-24, but otherwise considers this sensor unknown.

V.C.24.e. Unknown Eaton RADAR

Team 2004-24 stated: "The Eaton VORAD radar provides tracking data on up to 20 objects. This data includes azimuth, distance and closing speed." ([161], p. 5), but reported no additional identifying information. The "CW tone" of 24.5 GHz and "max power" of 50 mW reported by the team technical paper ([161]) does not conform to the "frequency" of 24.725 GHz and "transmitted RF power" of 3.0 mW reported by Eaton for either the VBOX or EVT-300 ([106] and [162]).

Searching the Eaton website for manufacturer product literature for other models of the VORAD RADAR with capabilities matching those reported by Team 2004-24 was ultimately unproductive. On January 5, 2009, Eaton sold the VORAD system to Bendix ([163]). Although Eaton reported Eaton's "Roadranger" organization will continue to support the VORAD system ([163]), and the VORAD system is a featured product at the online Roadranger "store", attempts to "click through" for VORAD products or literature terminated in pages stating: "For more information please contact your Roadranger Representative" and attempts to search for "VORAD" terminated in a page stating: "No items were found matching your search criteria.". Manufacturer product literature for the VORAD system was not available from Bendix.

The author concluded one Eaton RADAR was in use by Team 2004-24, but considers the model number of this sensor unknown.

V.C.24.f. Unknown magnetometers, gyroscopes, and accelerometers

Team 2004-24 stated: "The coarse heading sensor contains three magnetometers, three gyros and three accelerometers of moderate quality." ([161], p. 4), but reported no additional identifying information. The author concluded three magnetometers, three gyroscopes, and three accelerometers were in use by Team 2004-24, but otherwise considers these sensors unknown.

V.C.24.g. Unknown NavCom GPS receiver

Team 2004-24 stated: "Geolocation of the sensor platform is accomplished with the Navcom GPS and LN-200 inertial reference unit." ([161], p. 6), but reported no additional identifying information for the NavCom GPS receiver in use by the team. The author concluded one NavCom GPS receiver was in use by Team 2004-24, but considers the model number of this sensor unknown.

V.C.24.h. Team 2004-24 wheel speed sensors

Team 2004-24 stated: "For each motor and driver, a small custom board interfaces with the controlling PC 104 board and provides data on motor/wheel speed." ([161], p. 6).

The author considers the wheel speed sensors in use by Team 2004-24 known, but concluded the cost of these sensors cannot be independently determined.

V.C.25. Team 2004-25

- Team 2004-25 participated in the 2005 GCE as Team 2005-22. See paragraph V.C.46.
- The Team 2004-25 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-25 website was updated prior to the 2005 GCE, but reported no additional identifying information for the sensors in use by the team.

- Team 2004-25 passed on their turn on the second day of the 2004 QID ([84]), completed the 2004 QID course on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-25 was selected to participate in the 2004 GCE ([80]).

V.C.25.a. Japan Servo DME 60B6HF, unknown linear potentiometer, and Bodine Electric 42A-5N

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-25 stated: "The Challenge Vehicle uses optical encoders to determine the position and velocity of the brake, steering and throttle motors." ([49], p. 11). Team 2004-25 also stated: "The throttle is actuated by a 24 volt Japan Servo Company model DME 60B6HF permanent magnet dc gear motor with an integral encoder. The encoder provides throttle position feedback..." ([49], p. 2); "A linear potentiometer attached to the actuator provides feedback for the braking system." ([49], p. 3); and "Autonomous steering actuation is accomplished using a Bodine 24 volt permanent magnet right-angle gear motor (model 42A-5N) with an integral encoder (model 0941). ... As with the throttle and brake actuators, the encoder detects steering angle and feeds this information back to a motor controller." ([49], p. 3).

As a result, the author concluded: the optical encoder determining the position and velocity of the throttle motor was the integral encoder of the Japan Servo DME 60B6HF motor, and considers this sensor known; a linear potentiometer, in lieu of an optical encoder, was in use by Team 2004-25 for determining the position and velocity of the braking system linear actuator, and otherwise considers this sensor unknown; and the optical encoder determining the position and velocity of the steering motor was the integral encoder of the Bodine Electric 42A-5N motor, and considers this sensor known.

V.C.25.b. Unknown state sensors

In response to 2004 SQ 1.c.1 (see Table XXII), Team 2004-25 stated: "We also monitor the temperature of the electronic enclosure and battery voltage." ([49], p. 7). In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-25 stated: "Status sensors are used to monitor the health of the overall vehicle and its subsystems. As a minimum, we expect to monitor battery voltage for each on-board battery and the temperature inside all electronic enclosures." ([49], p. 11). Team 2004-25 also stated: "In addition, the vehicle carries a Yamaha 1600-watt gasoline powered AC generator that powers the AC computers and fans and indirectly charges two 12-volt lead acid batteries." ([49], p. 3), but reported no additional identifying information. The author concluded two "battery voltage" sensors were in use by Team 2004-25, but otherwise considers the "battery voltage" sensors unknown, and considers the temperature sensors in use by the team unknown.

V.C.25.c. Unknown thermal camera

In response to 2004 GCE SQ 2.b (see Table XXII), Team 2004-25 stated: “These tests will help us refine and integrate the laser rangefinder, thermal camera and radar systems.” ([49], p. 14), but reported no additional identifying information for the thermal camera in use by the team. Team 2004-25 does not make any other reference to a “thermal camera”; all other references to a camera are to a “visible light camera”. The author concluded no thermal camera was in use by Team 2004-25.

V.C.25.d. Unknown camera

Team 2004-25 stated: “...the Challenge Vehicle uses radar, laser rangefinders, and a visible light camera to sense local obstacles and discontinuities.” ([49], p. 8), but reported no additional identifying information for the visible light camera in use by the team. The author concluded one camera was in use by Team 2004-25, but otherwise considers this sensor unknown.

V.C.25.e. Unknown SICK LIDAR sensors

Figure 3 (“Computational Hardware Layout”) of the team technical paper ([49], p. 5) reported “2 LRF” (two laser range finders) were in use by Team 2004-25. However, Team 2004-25 stated: “Two laser rangefinders are mounted vertically from the roll cage of the vehicle. These laser rangefinders are used to detect obstacles in front of the vehicle. *The third laser rangefinder* is mounted on the brush guard in front of the vehicle.” ([49], pp. 9 - 10, *emphasis added*).

Team 2004-25 also stated: “Three Sick optic laser rangefinders, shown in Figures 10 and 11, actively scan the surroundings for obstacles. These units have a horizontal field of view of 90 degrees.” ([49], p. 9). Review of Figures 10 and 11 revealed the LIDAR sensor depicted by Figure 10 is a SICK LMS 200-30106 (“200-30106”) and the LIDAR sensor depicted by Figure 11 is either a LMS 211-30106 or -30206, or LMS 221-30106 or -30206. The SICK LMS 211-S14 (“211-S14”) has a scanning angle of 90 degrees ([74]); other models used by teams participating in the 2004 QID and GCE, including sensors matching those depicted by Figures 10 and 11 above, have a scanning angle of 100 or 180 degrees.

Although Team 2004-25 stated that three SICK LIDAR sensors were in use by the team, Team 2004-25 did not report the quantity of each depicted sensor or the model number for the SICK LIDAR sensors depicted by Figure 11, and the Team 2004-25 reported scanning angle does not conform to the manufacturer reported scanning angle for the potential sensors depicted. The author concluded three SICK LIDAR sensors were in use by Team 2004-25, but considers the quantities of each sensor depicted by Figures 10 and 11 and model number of the sensor depicted by Figure 11 unknown.

V.C.25.f. Unknown Eaton RADARs

Team 2004-25 stated: “Two Eaton VORAD radar units are mounted to the front of the Challenge Vehicle, each with a horizontal field of view of approximately 14 degrees.” ([49], p. 10), but reported no additional identifying information. Although the “horizontal field of view” of “approximately 14 degrees” reported by Team 2004-25 does not conform to the radar beam width of 12 degrees reported by Eaton, the “output power” of “3 mW” and “operating [frequency]” of “24.7 GHz” reported by Team 2004-25 conform to the transmitted RF power of 3.0 mW and frequency of 24.725 GHz reported by Eaton ([162]).

Neither Team 2005-22 nor its co-participant Team 2005-23 referred to RADAR sensors in use by the team ([58], [164], and [59]).

The author considers it was likely the Eaton EVT-300 was in use by Team 2004-25. However, in the absence of an affirmative statement from Team 2004-25 that the Eaton EVT-300 was in use by the team, the author concluded two Eaton RADARs were in use by Team 2004-25, but considers the model number of these sensors unknown.

V.C.25.g. Unknown Honeywell INS

Team 2004-25 stated: “The Challenge Vehicle uses a TALIN integrated DGPS/INS system from Honeywell for positioning.” ([49], p. 12), but reported no additional identifying information.

TALIN is an acronym for the Tactical Advanced Land Inertial Navigator (TALIN) product family, and multiple model numbers exist ([165]). Neither Team 2005-22 nor its co-participant Team 2005-23 referred to a Honeywell TALIN INS in use by the team ([58], [164], and [59]).

The author concluded one Honeywell INS was in use by Team 2004-25, but considers the model number of this sensor unknown.

V.C.25.h. Unknown wheel encoder

Team 2004-25 stated: “Actual speed, as determined from the DGPS/INS unit and a wheel encoder...” ([49], p. 9) and “A fourth encoder provides wheel velocity...” ([49], p. 11), but reported no additional identifying information. The author concluded one wheel encoder was in use by Team 2004-25, but otherwise considers this sensor unknown.

V.C.26. Team 2005-01

- Team 2005-01 participated in the 2004 GCE as Team 2004-02. See paragraph V.C.2.

- The Team 2005-01 website was updated prior to the 2007 Urban Challenge, and reported little additional identifying information for the sensors in use by the team.

- Team 2005-01 did not publish its results via the Journal of Field Robotics.

V.C.26.a. FLIR A20M and unknown AVT camera

Team 2005-01 stated: “[The challenge vehicle's Artificial Intelligence software] is utilized by [the challenge vehicle's] stereo cameras, thermal *cameras*, and RADAR.” ([10], p. 5, *emphasis added*), but reported no additional identifying information for the thermal cameras in use by the team. Via Table 1 (“Computing Hardware”) of the team technical paper ([10], p. 4), Team 2005-01 reported one color camera was in use by the team, but alternately stated: “The RSE also uses wiper blades to keep mud and rain from blocking the stereo and color *cameras*.” ([10], p. 9, *emphasis added*). Via Figure 4 (“Sensing & Stopping Distances”) of the team technical paper ([10], p. 9), Team 2005-01 reported one FLIR camera and one color camera were in use by the team.

Via Figure 2 (“Computing Systems”) of the team technical paper ([10], p. 5), Team 2005-01 reported two EMX Raytheon thermal cameras were in use by the team; Figure 2 did not report either the FLIR camera or color camera were in use by the team. Figure 2 of the Team 2005-01 technical paper ([10], p. 5) is virtually identical to Figure 2 of the Team 2004-02 technical paper ([9], p. 6).

Team 2005-01 alternately stated: “The RSE also uses wiper blades to keep mud and rain from blocking the stereo and color *cameras*.” ([10], p. 9, *emphasis added*) and “Other software used in [the challenge vehicle] comes from established vendors with a long history of application success. This software is utilized by [the challenge vehicle's] stereo cameras, thermal *cameras*, and RADAR.” ([10], p. 5, *emphasis added*). In addition, Team 2005-01 reported a FLIR camera was in use by the team, and stated: “High speed (400 Mbits/s) Red, Green, Blue (RGB) *cameras* are used mainly to enhance [the challenge vehicle's] ability to find road edges.” ([86], *emphasis added*).

As a result, the author concluded Figure 2 of the Team 2005-01 technical paper ([10]) was in error, that one color camera and one thermal camera were in use by Team 2005-01 despite several references to “cameras”, considers the FLIR camera in use by the team known based on the 2004 GCE published record and Figure 4 of the team technical paper ([10]), and considers the quantity and manufacturer of the color camera in use by the team known, but model number unknown, based on the 2004 GCE published record and Figure 4 of the team technical paper ([10]). See paragraph V.C.2.

V.C.26.b. Unknown Eaton RADAR, Amphitech OASys, and unknown RADARs

Team 2005-01 stated: “Other software used in [the challenge vehicle] comes from established vendors with a long history of application success. This software is utilized by [the challenge vehicle's] stereo cameras, thermal cameras, and RADAR." ([10], p. 5). Via Figure 4 ("Sensing & Stopping Distances") of the team technical paper ([10], p. 9), Team 2005-01 reported one "Eaton VORAD RADAR", one "Epsilon Lambda RADAR", and one "OASYS RADAR" were in use by the team. Team 2005-01 does not make any other reference to RADAR throughout the team technical paper ([10]) and reported no additional identifying information for the RADAR in use by the team.

In addition, Team 2005-01 reported RADAR in use by the team obliquely, via a page that could only be reached from the team website's site map. Team 2005-01 stated: "Eaton Vorad provides three of [the challenge vehicle's] seven RADAR units..." ([86]). A picture hosted by Team 2005-01 via the Team 2005-01 website denotes three sensors installed on the team challenge vehicle by red circles. The number on the hood of the challenge vehicle in the picture is "23", which was Team 2005-01's DARPA-assigned team number during the 2005 NQE. However, the resolution of this picture is limited, and the author was unable to identify the sensors in use by Team 2005-01. As a result, the author concluded one Eaton RADAR *system* utilizing three sensors, such as one antenna assembly and two side sensors, was in use by Team 2005-01 during the 2005 GCE, but considers the model number of this *system* unknown.

Team 2005-01 stated: "[The challenge vehicle's] RADAR range is from over 1 foot to 5 miles!" and "[The challenge vehicle] is using a Northrop Grumman LN-270 INS and an Amphitech OASYS 3D MWM RADAR..." ([86]). Team 2005-01 also stated: "[The Amphitech OASys] moves up and down and can see up to 5 miles in front of [the challenge vehicle]..." ([166]). The team website hosts a picture of the Amphitech OASys identical to the picture from the press release, but reported no additional information. As a result, the author concluded one Amphitech OASys was in use by Team 2005-01, and considers this sensor known.

Aside from Figure 4 of the team technical paper ([10], p. 9), Team 2005-01 did not refer to the Epsilon Lambda RADAR in use by the team, and a detailed search of the team website for additional detail was unsuccessful. Team 2005-01 stated seven RADAR units were in use by the team ([86]). The author considers it unlikely that three Epsilon Lambda RADARs were in use by Team 2005-01, although one Epsilon Lambda ELSC71-1A was in use by Team 2004-02 during the 2004 QID and GCE. As a result, the author considers additional RADARs in use by Team 2005-01 unknown.

V.C.26.c. SICK LMS 211-30206 and unknown SICK LIDAR sensors

Via Figure 4 of the team technical paper ([10], p. 9), Team 2005-01 reported three "SICK 291" LIDAR sensors and one "SICK 211" LIDAR sensor were in use by the team. Team 2005-01 stated: "If an obstacle is detected in the path, the vehicle detects this with either the four LADAR sensors or the five bumblebee cameras." ([10], p. 12), but reported no additional identifying information.

Team 2005-01 reported LIDAR sensors were in use by the team ([86]), but a detailed search of the team website for additional detail was unsuccessful.

The author considers the SICK LMS 211-30206 LIDAR sensor in use by Team 2005-01 known based on the 2004 GCE published record and Figure 4 of the team technical paper ([10], p. 9), and considers the quantity and manufacturer of the other SICK LIDAR sensors in use by Team 2005-01 known, but model numbers of these sensors unknown.

V.C.27. Team 2005-02

- Team 2005-02 participated in the 2004 GCE as Team 2004-04. See paragraph V.C.4.
- The Team 2005-02 website reported no additional identifying information for the sensors in use by the team.

Team 2005-02 stated: “An array of sensors including cameras, ladar, and radar are used for path modification due to obstacles and to acquire and track smooth terrain.” ([167], p. 2).

V.C.27.a. <u>SICK LMS 291-S05 LIDAR sensors</u>

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) and “Also, a third SICK ladar for planar obstacle detection ... [is] mounted on the front of the vehicle at bumper level.” ([167], p. 8), but reported no additional identifying information.

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) and “There are three Smart Sensors that rely on LADAR range data to produce their results: the Terrain Smart Sensor (TSS), the Negative Obstacle Smart Sensor (NOSS) and the Planar LADAR Smart Sensor (PLSS). All three components use the LMS291-S05 from Sick Inc. for range measurement.” ([50], p. 607).

The author concluded three SICK LMS 291-S05 LIDAR sensors were in use by Team 2005-02, and considers these sensors known.

V.C.27.b. Unknown Eaton RADAR

Team 2005-02 stated: "...a long-range Eaton Vorad radar for free space detection [is] mounted on the front of the vehicle at bumper level." ([167], p. 8), but reported no additional identifying information. In addition, Figure 2 ("System Architecture") of the team technical paper ([167], p. 4) reported a "VORAD Radar" was in use by Team 2005-02.

Team 2005-02 did not refer to the Eaton RADAR via the Journal of Field Robotics ([50]). Team 2005-02 stated: "Additional sensors were mounted on the vehicle for experimental purposes, but were not activated for the Darpa Grand Challenge (DGC) event. Each sensor system is described in detail later in this paper." ([50], p. 604).

The author concluded the unknown Eaton RADAR was not in use by Team 2005-02 during the 2005 GCE.

V.C.27.c. Unknown camera

Team 2005-02 stated: "These sensors include five cameras equipped with automatic iris. Two of these cameras are used for obstacle detection by stereo vision. The remaining three detect the path in a scene." ([167], p. 8). However, Team 2005-02 later stated: "The Pathfinder Smart Sensor (PFSS) consists of a single color camera mounted in the sensor cage and aimed at the terrain in front of the vehicle." ([50], p. 609).

Team 2005-02 reported no additional identifying information for the camera in use by the team. The author concluded one camera, in lieu of five, was in use by Team 2005-02, but otherwise considers this sensor unknown.

V.C.27.d. Smiths Aerospace North Finding Module

Team 2005-02 stated: "The processing of all navigation data is done by a Smiths Industries Northfinding Module (NFM), which is an inertial navigation system. This module maintains Kalman Filter estimates of the vehicle's global position, orientation, as well as linear and angular velocites [*sic*]. It fuses internal accelerometer and gyroscope data, with data from an external NMEA GPS and external odometer." ([167], p. 6) and "In summary, the Smith's IMU fuses and filters information from the NavCom or Garmin GPS, as well as a vehicle odometer." ([167], p. 7).

The author was unable to locate a manufacturer named "Smiths Industries", but a manufacturer named "Smiths Aerospace" existed at the time of the 2004 QID and GCE, and has since been acquired by GE.

Team 2005-02 later stated: "The processing of all navigation data is done by a Smiths Aerospace North-finding Module (NFM), which is an inertial navigation system. This module maintains Kalman filter estimates of the vehicle's global position and orientation, as well as linear and angular velocities. It fuses internal accelerometer and gyroscope data, with data from an external NMEA GPS, and external odometer." ([50], p. 607).

Without GPS integration, the "north finding" module determines azimuth only. Although GE stated the North Finding Module adds "GPS/Inertial Kalman Filter Solution" and "Inertial or GPS backup" ([168]), the author does not consider a North Finding Module to be either an INS or an IMU. However, the author concluded one Smiths Aerospace North Finding Module was in use by Team 2005-02, and considers this sensor known.

V.C.27.e. Unknown NavCom GPS receiver

Team 2005-02 stated: "The GPS signal provided to the (NMF) [*sic*] comes from one of the two sensors onboard. These include a NavCom Technologies Starfire 2050..." ([167], p. 6), but reported no additional identifying information.

Team 2005-02 later stated: "The GPS signal provided to the NFM comes from one of the two onboard sensors. These include a NavCom Technologies Starfire 2050..."([50], p. 607), but reported no additional identifying information.

The NavCom StarFire SF-2050 GPS receiver and StarFire network were in use by 12 of 40 NQE semifinalists ([102]) and 6 of 23 GCE finalists ([103]). At least two different NavCom StarFire models existed at the time of the 2005 GCE, and they targeted different markets: "The SF-2050G is designed for backpack GIS and mapping applications while the SF-2050M is ideal for vehicle mounting to suit a wide variety of machine guidance and control applications." ([104]). NavCom launched both the SF-2050G and SF-2050M receivers in 2002 ([105]). The author concluded one NavCom GPS receiver was in use by Team 2005-02, but considers the model number of this sensor unknown.

V.C.28. Team 2005-03

- Team 2005-03 participated in the 2004 QID and GCE as Team 2004-06. See paragraph V.C.6.

- The Team 2005-03 website was no longer available.

- Team 2005-03 did not publish its results via the Journal of Field Robotics.

V.C.28.a. Proprietary LIDAR sensor

Team 2005-03 stated: "A unique LADAR terrain mapping and obstacle detection system is employed as the single sensor." ([33], p.7), but reported no additional identifying information.

The author considers the proprietary LIDAR sensor in use by Team 2005-03 known, but concluded the cost of this sensor cannot be independently determined.

V.C.28.b. NavCom SF-2050G and NovAtel ProPak-LBplus

Team 2005-03 stated: "Dual GPS receivers are used, both to establish direction at rest and to provide redundancy. The first is a Navcom 2050G using the Starfire subscription service and the second is a Novatel ProPak-LB receiver using the Omnistar subscription service." ([33], p. 7).

The author concluded one NavCom SF-2050G and one NovAtel ProPak-LBplus[21] were in use by Team 2005-03, and considers these sensors known.

V.C.28.c. Unknown IMU

Team 2005-03 stated: "Also, there is a 6-axis inertial system mounted on the LADAR head (described below) that is used to correct the LADAR signal as well as provide pitch and roll information for correcting the FOG gyro signal. The third gyro in the 6-axis system is used as a redundant backup for the FOG gyro. " ([33], p. 7), but reported no additional identifying information for the "6-axis inertial system" in use by the team. The author considers it likely Team 2005-03 was referring to 6DOF, in lieu of "6-axis", and concluded one IMU was in use by Team 2005-03, but otherwise considers this sensor unknown.

V.C.28.d. Honeywell TALIN-4000

Team 2005-03 stated: "Additionally, there is a Honeywell TALON-4000 unit that might be installed by race time." ([33], p. 7). Honeywell did not manufacture a model number "TALON-4000". TALIN is an acronym for the Tactical Advanced Land Inertial Navigator (TALIN) product family, and the correct model number is "TALIN-4000" ([165]). The author concluded "TALON-4000" was an error and that Team 2005-03 was referring to the Honeywell TALIN-4000, and considers this sensor known. However, Team 2005-03 stated this sensor "might be installed by race time". In the absence of an affirmative statement by Team 2005-03 that the Honeywell TALIN-4000 was in use during the 2005 GCE, the author concluded this sensor was not in use during the 2005 GCE.

V.C.29. Team 2005-04

- The Team 2005-04 website reported no additional identifying information for the sensors in use by the team.
- Team 2005-04 published its results via the Journal of Field Robotics, however Team 2005-04 reported no additional identifying information for the sensors in use by the team via the Journal of Field Robotics.

Team 2005-04 stated: "A set of sensors (LIDAR's, radars, cameras and ultrasonic transducers) and a GPS and IMU unit provide extensive sensing capability." ([169], p. 2) and "[The challenge vehicle] has LIDAR's, radars, cameras and ultrasonic sensors to sense its immediate surroundings." ([169], p. 8).

V.C.29.a. NovAtel ProPak-LBplus

Team 2005-04 stated: "The GPS used is a Novatel Propak LB-L1L2 with Omnistar HP differential correction." ([169], p. 7)[21]. The author concluded one NovAtel ProPak-LBplus was in use by Team 2005-04, and considers this sensor known.

V.C.29.b. Unknown RADAR

Team 2005-04 stated: "The second radar has a slewing dish antenna and is an in-house development." ([169], p. 8), but reported no additional identifying information. The author concluded one "second radar" was in use by Team 2005-04 and that Team 2005-04 was the manufacturer of this sensor, but considers the model number of this sensor unknown, and concluded the cost of this sensor cannot be independently determined.

V.C.29.c. Unknown stereo camera pair

Team 2005-04 stated: "The stereo camera system is mounted on the top and again pointed ahead." ([169], pp. 8 - 9), but reported no additional identifying information. The author concluded one stereo camera pair was in use by Team 2005-04, but otherwise considers this sensor unknown.

V.C.29.d. Unknown ultrasonic range finders

Team 2005-04 stated: "8 ultrasonic rangefinders are mounted around the vehicle and are for short distance sensing at low speeds, and in particular for sensing in confined areas when the vehicle is operating at low speeds and potentially without accurate position information." ([169], p. 9), but reported no additional identifying information. The author concluded eight ultrasonic range finders were in use by Team 2005-04, but otherwise considers these sensors unknown.

V.C.29.e. Wheel speed sensors

Team 2005-04 stated: "Localization, vehicle motion status, and internal state sensing is accomplished using ... wheel speed sensors that were added to the vehicle..." ([169], p. 11), but reported no additional identifying information. The author estimated the quantity of wheel speed sensors in use by Team 2005-04 in accordance with paragraph V.B.5.c., but otherwise considers these sensors unknown.

V.C.30. Team 2005-05

- Team 2005-05 participated in the 2004 QID and GCE as Team 2004-07. See paragraph V.C.7.

- The Team 2005-05 website reported limited additional identifying information for the sensors in use by the team.

The Team 2005-05 technical paper ([34]) described two vehicles. However, only one of the two vehicles participated in the 2005 GCE as the challenge vehicle. The discussion that follows is based on the Team 2005-05 challenge vehicle.

Team 2005-05 stated: "Our sensing strategy is to use Sick laser measurement systems ('ladars') to detect significant positive and negative obstacles (roughly defined as too-abrupt changes of apparent ground elevation), and a Mobileye Pathfinder vision system to detect the edges of the road or trail." ([34], p. 5).

V.C.30.a. Unknown SICK LIDAR sensors

Team 2005-05 stated: "Each [challenge vehicle] has one or more Sick LMS-291 ladars..." ([34], p. 5). Via Figure 2 ("Arrangement of vertical-plane Sick LMS-291 ladars on the Golem vehicles") of the team technical paper ([34], p. 6), Team 2005-05 reported the challenge vehicle had three "vertical-plane Sick LMS-291 ladars". Team 2005-05 also stated: "We also use a Sick LMS-221 which sweeps its beam in a horizontal plane through a 180-degree arc of azimuth. It can be supplemented by a Sick LMS-291 which sweeps a 90-degree arc in a horizontal plane at a different height." ([34], p. 6). Team 2005-05 did not report whether the horizontal plane LIDAR sensors were in use on one, the other, or both vehicles, or even if the supplemental horizontal plane LIDAR sensor was in use by the team.

Team 2005-05 later stated: "The sensors used for terrain perception included a Sick LMS-221 ladar... There were also four Sick LMS-291 ladars..." ([170], p. 529), but did not report the model number for the LIDAR sensors in use by the team. The team website reported no additional identifying information for the LIDAR sensors in use by the team.

As a result, the author concluded five SICK LIDAR sensors were in use by Team 2005-05, but considers the model numbers of these sensors unknown.

V.C.30.b. Mobileye ACP5

Team 2005-05 stated: "Our sensing strategy is to use ... a Mobileye Pathfinder vision system to detect the edges of the road or trail." ([34], p. 5); "Mobileye's Pathfinder system is a vision system using images from a forward looking camera to detect paved road or unpaved trail boundaries using intensity contrast information and texture analysis." ([34], p. 8); and "The prototype system developed by Mobileye uses a miniature lipstick analog CCD camera with a typical 45 degree horizontal field of view for acquiring video images." ([34], p. 8).

The "Pathfinder system" was an application designed to leverage an existing product, the Mobileye ACP5 On-Line Vision System ([171]). The Pathfinder system may no longer be in production and the ACP5 is not a current "Manufacturer Product". The author concluded one Mobileye ACP5 was in use by Team 2005-05, and considers this sensor known.

V.C.30.c. NovAtel ProPak-LBplus

Team 2005-05 stated: "[The challenge vehicles] each use a NovAtel Propak-LBPlus receiver for GPS positioning with Omnistar HP correction. During our development process we also had good results using a Trimble AgGPS 114 receiver with Omnistar VBS correction." ([34], p. 5).

Team 2005-05 later stated: "The sensors mounted on [the challenge vehicle] ... included a Novatel ProPak LB-Plus differential GPS receiver with nominal 14-cm accuracy using OmniStar HP correction..." ([170], p. 529).

The author concluded one NovAtel ProPak-LBplus[21], in lieu of a Trimble AgGPS 114, was in use by Team 2005-05, and considers this sensor known.

V.C.30.d. Systron Donner C-MIGITS III

Team 2005-05 stated: "A C-MIGITS III inertial navigation system from BEI Technologies is used to track changes in orientation." ([34], p. 5).

Team 2005-05 later stated: "The sensors mounted on [the challenge vehicle] ... included ... a BEI C-MIGITS inertial measurement unit (IMU)..." ([170], p. 529).

The C-MIGITS III IMU is a product of Systron Donner, which is a division of BEI. The author concluded one Systron Donner C-MIGITS III was in use by Team 2005-05, and considers this sensor known.

V.C.30.e. Unknown Hall Effect sensor

Team 2005-05 stated: "During GPS outages we continue to track position using the C-MIGITS III and measurements of wheel rotation and steering angle." ([34], p. 5) and "A Hall sensor and a ring of magnets attached to the rear differential form a high-accuracy odometer that measures revolutions of the rear axle." ([34], p. 11).

Team 2005-05 later stated: "The sensors mounted on [the challenge vehicle] ... included ... a custom Hall encoder on the differential for odometry with approximately 10-cm accuracy..." ([170], p. 529).

The author concluded one Hall Effect sensor was in use by Team 2005-05, but otherwise considers this sensor unknown.

V.C.31. Team 2005-06

- The hyperlink to the Team 2005-06 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to another website, which was no longer available.

V.C.31.a. <u>Oxford RT3000</u>

Team 2005-06 stated: "[Team 2005-06] chose to use the RT3000 from Oxford Technical Solutions to provide vehicle localization." ([172], p. 8) and "[Team 2005-06] 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 2005-06 later stated: "The position and pose of [the challenge vehicle] is reported by an Oxford Technical Solutions RT3000, an integrated GPS with two antennas and an Inertial Navigation System (INS)." ([28], p. 513).

The author concluded, although Team 2005-06 may have installed two Oxford RT3000 sensors for redundancy, only one at a time was in use during the 2005 GCE, and considers this sensor known.

V.C.31.b. <u>Unknown stereo camera pair</u>

Team 2005-06 stated: "Stereographic cameras capable of producing a three-dimensional point cloud are also mounted on the front of the vehicle behind the windshield. These cameras operate in a secondary mode to the LADAR units, and they are only used to help identify the road and to confirm the existence of obstacles." ([172], p. 9), but reported no additional identifying information.

Team 2005-06 later stated: "While other sensors were considered for inclusion into the vision system, their contributions were not considered useful enough to warrant the complications they would have added to the sensor fusion algorithms." ([28], p. 525). The author concluded the stereo camera pair was not in use by Team 2005-06 during the 2005 GCE.

V.C.31.c. <u>Riegl LMS-Q120 and unknown SICK LIDAR sensors</u>

Team 2005-06 stated: "[Team 2005-06] has mounted three Sick LMS 291 LADAR units and one RIEGL LMS-Q120 LADAR on the front of its vehicle." ([172],

p. 9), but did not report the model number of the SICK LIDAR sensors in use by the team.

Team 2005-06 later stated: “Two Sick LMS 291 Laser Detecting and Ranging (LADAR) devices provided the autonomous vehicle with environmental sensing.” ([28], p. 513), but did not report the model number of the SICK LIDAR sensors in use by the team or report the Riegl LMS-Q120 was in use during the 2005 GCE.

The author concluded the Riegl LMS-Q120 was not in use by Team 2005-06 during the 2005 GCE and that two SICK LIDAR sensors were in use by the team, but considers the model number of these sensors unknown.

V.C.31.d. Unknown wheel speed sensor

Team 2005-06 stated: “The RT3000 also accepts additional custom inputs to reduce drift in its estimate of vehicle position when GPS is not available. ... One of these custom inputs is a wheel speed sensor which provides TTL pulses based upon an encoder placed on a single wheel on the vehicle.” and “The wheel speed sensor consisted of a digital sensor capable of detecting either ferrous metal or magnets that are in motion.” ([28], p. 513). The author concluded one wheel speed sensor was in use by Team 2005-06, but otherwise considers this sensor unknown.

V.C.32. Team 2005-07

- Team 2005-07 participated in the 2004 QID as Team 2004-08. See paragraph V.C.8.

- The Team 2005-07 website reported no additional identifying information for the sensors in use by the team.

- The hyperlink to the Team 2005-07 technical paper 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 paper on the team website. As a result, the author concluded the technical paper was unavailable for review.

- Team 2005-07 did not publish its results via the Journal of Field Robotics.

V.C.32.a. Unknown SICK LIDAR sensors, unknown GPS receiver, and unknown cameras

Team 2005-07 published a description of their challenge vehicle via the team website ([118]), and the caption of a picture embedded in this reference reported SICK LIDAR sensors, cameras, and a GPS receiver were in use by the team. Team 2005-07 stated: “Commercial camcorders that provide image stabilization collect video from inside the vehicle allowing both 2 dimensional and stereo scene analysis.” and “We use two SICK Lidar units to monitor the terrain in front of the moving vehicle." ([118]). Team 2005-07 did not report the model number of the SICK LIDAR sensors in use by the team, or the quantity, manufacturer, or model number of the cameras or GPS receiver.

As a result, the author concluded two SICK LIDAR sensors were in use by Team 2005-07, but considers the model number of these sensors unknown; estimated one GPS receiver was in use by Team 2005-07, but otherwise considers this sensor unknown; and considers the cameras in use by Team 2005-07 unknown.

V.C.33. Team 2005-08

- The Team 2005-08 website was no longer available.
- Team 2005-08 did not publish its results via the Journal of Field Robotics.

V.C.33.a. <u>SICK LMS 291-S14 and SICK LMS 211-30106</u>

Via Figure 1 ("F250 Platform") of the team technical paper ([173], p. 4), Team 2005-08 reported a "Vertical SICK" and a "Profile SICK" were in use by the team. However, via Figure 2 ("Hardware Configuration") of the team technical paper ([173], p. 7), Team 2005-08 reported three SICK sensors were in use by the team. Figure 6 ("Sensor position and envelopes") of the team technical paper ([173], p. 12) reported "sensor position and envelope" for the profile SICK referred to by Figure 1.

Team 2005-08 stated: "A combination of SICK LMS line scan ladar units are used for close range terrain sensing on [the challenge vehicle]. The LMS 290-S14 (90 deg at 0.5 deg/pixel with 75Hz scan rate) mounted in the roof sensor suite is used to provide a vertical slice of the terrain in front of the vehicle for assessment of the support surface, especially in undulating terrain. The LMS 211-30106 (180 deg at 1 deg/pixel with 75Hz scan rate) mounted on the front sensor rack is used both for profile following and hazard detection." ([173], p. 9).

Three SICK LIDAR sensors had model numbers ending in "-S14" at the time of the 2005 GCE ([75]): LMS 211-S14, 221-S14, and 291-S14. Based on its use by other teams, the author concluded "LMS 290-S14" was an error, and that the sensor in use by Team 2005-08 was a SICK LMS 291-S14, and considers this sensor known.

In addition, the author concluded two SICK LIDAR sensors were in use by Team 2005-08, in lieu of three reported via Figure 2 of the team technical paper, and that a SICK LMS 211-30106 was the second SICK LIDAR sensor, and considers this sensor known.

V.C.33.b. Unknown ultrasonic sensors

Team 2005-08 stated: “Ultrasonic sensors are present at the four corners of the vehicle covering the left and right sides at close range for tunnel following.” ([173], p. 11), but reported no additional identifying information.

The author concluded four ultrasonic sensors were in use by Team 2005-08, but otherwise considers these sensors unknown.

V.C.33.c. Unknown Vansco RADAR

Team 2005-08 reported a “Vansco Doppler radar sensor” was in use by the team ([173], p. 8). Vansco manufactured a “740 Radar” product ([174]).

However, the author was unable to confirm this model number was current at the time of the 2005 GCE, and concluded one Vansco RADAR was in use by Team 2005-08, but considers the model number of this sensor unknown.

V.C.33.d. Sony DFW-VL500 and unknown cameras

Via Figure 1 (“F250 Platform”) of the team technical paper ([173], p. 4), Team 2005-08 reported “Road Following Color Cameras” were in use by the team. Via Figure 2 (“Hardware Configuration”) of the team technical paper ([173], p. 7), Team 2005-08 reported four cameras were in use by the team, two as a stereo camera pair. Figure 6 (“Sensor position and envelopes”) of the team technical paper ([173], p. 12) reported “sensor position and envelope” for the road-following cameras referred to by Figure 1.

Team 2005-08 stated: “A fixed baseline stereo pair of firewire color cameras (Sony DFW-VL500) is located on the front sensor rack to provide dense local range data.” ([173], p. 11). Team 2005-08 reported no additional identifying information for the two road-following cameras in use by the team.

The author concluded two Sony DFW-VL500 cameras were in use by Team 2005-08 as a stereo camera pair, and considers these sensors known. The author concluded two “road-following” cameras were in use by Team 2005-08, but otherwise considers these sensors unknown.

V.C.33.e. Unknown active bumper

Team 2005-08 stated: “An active bumper is integrated into the front sensor rack to provide a last line of response for protection of vehicle hardware and a means to recover from sensing and planning errors that could place the vehicle in contact with obstacles.” ([173], p. 11), but reported no additional identifying information.

The author concluded one active bumper was in use by Team 2005-08, but otherwise considers this sensor unknown.

V.C.34. Team 2005-09

- The hyperlink to the Team 2005-09 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to a URL which resulted in a "404 File Not Found" error. However, a search of that domain revealed the Team 2005-09 website was relocated to an alternate URL on the same domain. The Team 2005-09 website reported no additional identifying information for the sensors in use by the team.

V.C.34.a. Unknown SICK LIDAR sensors

Team 2005-09 stated: "Eight SICK laser range finders provide a two-dimensional range/distance map up to 40 meters with a 100 degree field of view. Two vertically mounted lasers provide ground plane information. Three lasers are mounted horizontally at different angles allowing for both short and long range detection of road obstacles. A fourth laser is mounted on a gimbal that allows for dynamic pointing in order to compensate for vehicle pitch and terrain variations. Finally, two downward looking lasers are mounted on the roof to derive road characteristics." ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: "The sensing centers around eight laser sensors were [*sic*] oriented in different directions and mounted on the top and front of the vehicle..." and "Two vertically mounted lasers provide information about the ground plane. Three lasers, mounted horizontally at different angles, provide both short- and long-range detection of road obstacles. A sixth horizontal laser is mounted on gimbals, and points dynamically to compensate for vehicle pitch and terrain variations. Finally, two downward-looking lasers are mounted on the roof to detect road characteristics." ([52], p. 813), but reported no additional identifying information.

The author concluded eight SICK LIDAR sensors were in use by Team 2005-09, but otherwise considers these sensors unknown.

V.C.34.b. Unknown Eaton RADAR

Team 2005-09 stated: "Additional sensors include an Eaton Vorad doppler range rate radar developed for the trucking industry." ([175], p. 8), but reported no additional identifying information.

Team 2005-09 later stated, in a series of goals prior to the 2005 GCE: "May. Prepare for a DARPA site visit. Testing had moved from obstacle avoidance to finding a balance between speed, planning, and reaction time. At this point, sensing strategies were unresolved with stereo vision, radar, and machine vision for road detection under consideration." ([52], p. 831). Team 2005-09 did not refer to the Eaton RADAR elsewhere throughout the Journal of Field Robotics ([52]), or report RADAR was in use by the team during the 2005 GCE.

The author concluded the unknown Eaton RADAR was not in use by Team 2005-09 during the 2005 GCE.

V.C.34.c. Unknown stereo camera pair and unknown machine vision system

Team 2005-09 stated: “In addition to the obstacle detection sensors, [the challenge vehicle] has a vision system to detect the edges of and center of the road.” ([175], p. 8), but reported no additional identifying information.

Team 2005-09 later stated, in a series of goals prior to the 2005 GCE: “May. Prepare for a DARPA site visit. Testing had moved from obstacle avoidance to finding a balance between speed, planning, and reaction time. At this point, sensing strategies were unresolved with stereo vision, radar, and machine vision for road detection under consideration.” ([52], p. 831). Team 2005-09 did not refer to “stereo vision” or “machine vision” system elsewhere throughout the Journal of Field Robotics ([52]), or report a stereo camera pair or machine vision system were in use by the team during the 2005 GCE.

The author concluded the unknown stereo camera pair and unknown machine vision system were not in use by Team 2005-09 during the 2005 GCE.

V.C.34.d. Trimble AgGPS 132 DGPS receivers

Team 2005-09 stated: “Two Trimble GPS systems provide submeter accuracy through an Omnistar subscription.” ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: “The primary GPS receivers are two Trimble AgGPS132 differential GPS units, with differential corrections from the Omnistar subscription service.” ([52], p. 817).

The author concluded two Trimble AgGPS 132 DGPS receivers were in use by Team 2005-09, and considers these sensors known.

V.C.34.e. Microbotics MIDG-II

Team 2005-09 stated: “A third GPS is provided by a MIDG-2 inertial navigation system that comes from the remote controlled plane community.” ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: “A third GPS is a MIDG-2 INS.” ([52], p. 819), but reported no additional identifying information.

An Internet search using the key words “+'MIDG-2' +ins +gps” as the search string revealed the MIDG-II INS/GPS is a Microbotics product. The author concluded one Microbotics MIDG-II was in use by Team 2005-09, and considers this sensor known.

V.C.34.f. Unknown Honeywell compass

Team 2005-09 stated: "...a Honeywell magnetic compass is used as an alternative source of heading." ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: "Two sensor racks were built to mount the sensors to the outside of the vehicle. The largest sensor rack is mounted on top of the vehicle. It provides the platform for mounting the global positioning system (GPS) receivers, inertial navigation system (INS), and magnetic compass." ([52], p. 813); "Positioning is by three GPS units, an INS unit and a compass on the roof." ([52], p. 814); and "Initially, a Honeywell magnetic compass provided an alternative source of heading. However, it was abandoned because it required calibration in different locations (Nevada and California), had high latency (degrees per minute), and drifted as much as 10º with the vehicle stopped." ([52], p. 819). Team 2005-09 did not refer to a compass in use by the team elsewhere throughout the Journal of Field Robotics ([52]).

The author concluded the unknown Honeywell compass was not in use by Team 2005-09 during the 2005 GCE.

V.C.34.g. Unknown encoders

Team 2005-09 stated: "Additionally, shaft encoders provide odometry at very slow speeds providing information that is needed for dead reckoning." ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: "Vehicle displacement is measured via a multielement quadrature shaft encoder, mounted directly to the vehicle drive shaft. We assume no differential slip or tire slip. A similar encoder is mounted to the steering column, and provides steering wheel angle." ([52], p. 819), but reported no additional identifying information.

The author concluded one "quadrature shaft encoder" was in use by Team 2005-09 to measure "vehicle displacement" and one "encoder" was in use by Team 2005-09 to measure "steering wheel angle", but otherwise considers these sensors unknown.

V.C.35. Team 2005-10

- The Team 2005-10 website was no longer available.
- Team 2005-10 did not publish its results via the Journal of Field Robotics.

V.C.35.a. Unknown SICK LIDAR sensors

Team 2005-10 stated: "Two SICK LMS-291 2 dimensional laser range finders." ([176], p. 3), but did not report the model number of these sensors.

The author concluded two SICK LIDAR sensors were in use by Team 2005-10, but considers the model number of these sensors unknown.

V.C.35.b. Cognex DVT 542C cameras

Team 2005-10 stated two "DVT 542C color cameras" were in use by the team ([176], p. 3). Cognex acquired DVT in May, 2005 ([177] and [178]). DVT 542C is not a current Cognex model number ([179]), but a model number DVT 542C was offered by Cognex through 2006 ([180]).

The author concluded two Cognex DVT 542C cameras were in use by Team 2005-10, and considers these sensors known.

V.C.35.c. Unknown stereo camera pair

Team 2005-10 reported one stereo camera pair was in use by the team ([176], p. 3), and stated: "Stereo vision was the most difficult data analysis challenge, but in the end, has become a very useful sensor. Using a unique and proprietary algorithm, we are able to use the fast, 30 frames per second, update rate from the stereo vision camera and detect most obstacles easily." ([176], p. 7).

The author concluded one stereo camera pair was in use by Team 2005-10, but otherwise considers this sensor unknown.

V.C.35.d. NavCom SF-2050G

Team 2005-10 stated a "Navcom Starfire™ 2050G" was in use by the team ([176], p. 3).

NavCom manufactured a model number SF-2050G. The author concluded "2050G" was an incomplete model number and that Team 2005-10 was referring to a NavCom SF-2050G, and considers this sensor known.

V.C.35.e. Unknown Kearfott INS

Team 2005-10 reported one "Kearfott MIL-NAV inertial navigation unit" was in use by the team ([176], p. 4), but reported no additional identifying information.

"MILNAV" is an acronym for "Miniature Integrated Land Navigation System" ([181]). The MILNAV has a manufacturer product family of KN-4050, however multiple model numbers within this product family existed.

The author concluded one Kearfott INS was in use by Team 2005-10, but considers the model number of this sensor unknown.

V.C.35.f. Unknown Crossbow accelerometer

Team 2005-10 stated: “One Crossbow 3 axis accelerometer measures G forces in the X, Y and Z direction.” ([176], p. 3), but reported no additional identifying information.

The author concluded one Crossbow accelerometer was in use by Team 2005-10, but considers the model number of this sensor unknown.

V.C.36. Team 2005-11

- Team 2005-11 did not publish its results via the Journal of Field Robotics.
- The hyperlink to the Team 2005-11 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to a URL which resulted in a “HTTP 404 - File not found” error. However, a search of that domain revealed the Team 2005-11 website was relocated to an alternate URL on the same domain. The Team 2005-11 website reported no additional identifying information for the sensors in use by the team.

V.C.36.a. Unknown SICK LIDAR sensors

Team 2005-11 stated: “Three to four SICK LMS 291 LIDAR units are deployed at various fixed locations and orientations on [the challenge vehicle].” ([182], p. 7), but reported no additional identifying information.

The author concluded the manufacturer of the SICK LIDAR sensors in use by Team 2005-11 was known, but otherwise considers these sensors unknown.

V.C.36.b. Unknown Crossbow INS

Team 2005-11 stated: “A Crossbow Navigation Attitude Heading Reference System (NAHRS) module is the main navigation and guidance application.” ([182], p. 7), but reported no additional identifying information.

The Team 2005-11 description matches multiple product series with multiple model numbers ([96]). The author concluded one Crossbow INS was in use by Team 2005-11, but otherwise considers this sensor unknown.

V.C.36.c. Unknown NovAtel GPS receiver

Team 2005-11 stated: “This system augments the Crossbow navigation solution with input from a decimeter accurate Novatel GPS receiver with Omnistar capability.” ([182], p. 7), but reported no additional identifying information.

The author concluded one NovAtel GPS receiver was in use by Team 2005-11, but otherwise considers this sensor unknown.

V.C.36.d. Unknown wheel speed sensors

Team 2005-11 stated: "The master navigation filter under certain situations also employs odometry data from the wheels." ([182], p. 7) and "Wheel speed sensors are used to control [the challenge vehicle's] antilock brakes." ([182], p. 8), but reported no additional identifying information.

The author did not estimate the quantity of wheel speed sensors in accordance with paragraph V.B.5.c., and considers these sensors unknown.

V.C.37. Team 2005-12

- Team 2005-12 published its 2005 GCE results via the Journal of Field Robotics ([183]).
- No hyperlink to the Team 2005-12 website was hosted by DARPA via the Archived Grand Challenge 2005 website ([19]). However, an Internet search using the key words "+'princeton' +darpa +'grand challenge'" as the search string revealed a team website existed ([184]). The Team 2005-12 website reported no additional identifying information for the sensors in use by the team.

V.C.37.a. Unknown Trimble DGPS receiver

Team 2005-12 stated: "A Trimble DGPS unit (using WAAS) provides position data..." ([185], p. 5), but reported no additional identifying information.

Team 2005-12 referred to "GPS" throughout the Journal of Field Robotics ([183]), but reported no additional identifying information for the Trimble DGPS receiver in use by the team.

The author concluded one Trimble DGPS receiver was in use by Team 2005-12, but otherwise considers this sensor unknown.

V.C.37.b. Unknown CoPilot GPS receiver

Team 2005-12 stated: "A CoPilot GPS unit is used as a backup receiver." ([185], p. 5), but reported no additional identifying information.

Team 2005-12 referred to "GPS" throughout the Journal of Field Robotics ([183]), but reported no additional identifying information for the CoPilot GPS receiver in use by the team.

ALK reported "CoPilot GPS" is the name of a family of software products developed by ALK ([186]). The author did not record the ALK CoPilot GPS software in Table XXVIII because it is a software product, not a navigation sensor.

The CoPilot GPS software requires the use of a GPS receiver, such as the "CoPilot USB GPS Receiver" ([186]). However, in the absence of a definitive statement from the team, the author concluded neither the ALK CoPilot GPS software nor accompanying GPS receiver was in use by Team 2005-12 during the 2005 GCE.

V.C.37.c. Unknown encoder

Via an un-numbered and un-titled figure ([185], p. 4), Team 2005-12 reported one "Steering Wheel Position Encoder" and "ABS Wheel Encoders" were in use by the team. Team 2005-12 stated: "An optical digital position encoder is used for precise position feedback." ([185], p. 3).

Team 2005-12 later stated: "An optical rotary encoder, also attached to the steering wheel, provides precise position feedback." ([183], p. 746). Team 2005-12 did not refer to "wheel encoder" or "ABS" throughout the Journal of Field Robotics ([183]).

The author concluded one "optical rotary encoder" was in use by Team 2005-12 to provide "precise position feedback" during the 2005 GCE, but otherwise considers this sensor unknown. Due to the difficulty other teams reported adapting existing OEM sensors to other uses (e.g., OBD-II), and in the absence of a definitive statement from the team, the author concluded the "ABS Wheel Encoders" were not in use by Team 2005-12 during the 2005 GCE.

V.C.37.d. Unknown compass

Via an un-numbered and un-titled figure ([185], p. 4), Team 2005-12 reported one "Compass" was in use by the team. Team 2005-12 did not refer to "compass" throughout the Journal of Field Robotics ([183]).

The author concluded the compass was not in use by Team 2005-12 during the 2005 GCE.

V.C.38. Teams 2005-13 and 2005-14

- Team 2005-13 participated in the 2004 QID and GCE as Team 2004-10. See paragraph V.C.10.
- Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE, and published their results jointly via the Journal of Field Robotics ([24]).
- The Teams 2005-13 and 2005-14 website reported no additional identifying information for the sensors in use by the team.

V.C.38.a. Riegl LMS-Q140i and unknown SICK LIDAR sensors

Throughout the team technical papers ([11] and [12]), Teams 2005-13 and 2005-14 referred to "LIDAR", "LIDAR line scanner", "short range LIDAR", "short range LIDAR line scanner", "long range LIDAR", "long Range LIDAR line scanner", and "long range single line LIDAR".

Via Table 2 of the team technical papers ([11], p. 9 and [12], p. 9), Teams 2005-13 and 2005-14 reported one long-range LIDAR sensor and six short-range LIDAR sensors were in use by the teams.

Teams 2005-13 and 2005-14 stated: "Four (4) short range LIDAR line scanners ... are mounted on ... the vehicle. ... Two (2) short range LIDARs are mounted on the shock isolated electronics bay." ([11], p. 8) and "Four (4) short range LIDAR line scanners ... are mounted on ... the vehicle. ... Two short range LIDARs are mounted ... on the superstructure of the roof." ([12], p. 8).

Teams 2005-13 and 2005-14 later stated: "A Riegl Q140i scanning laser range finder is used as the primary terrain perception sensor for both robots..." ([24], p. 476) and "...four SICK LMS 291 laser scanners are used to provide short-range supplemental sensing." ([24], p. 477), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

The author concluded one Riegl LMS-Q140i was in use by Teams 2005-13 and 2005-14, and considers this sensor known; and, because the Journal of Field Robotics ([24]) represents the final written report of Teams 2005-13 and 2005-14, concluded four SICK LIDAR sensors, in lieu of six, were in use by Teams 2005-13 and 2005-14, but considers the model number of these sensors unknown.

V.C.38.b. Navtech DS2000

Throughout the team technical papers ([11] and [12]), Teams 2005-13 and 2005-14 referred to "RADAR", "360 degree RADAR", and "360º RADAR".

Teams 2005-13 and 2005-14 later stated: "...the NavTech DS2000 continuous-wave frequency modulated (CWFM) radar was used as a complimentary [*sic*] sensor to the LIDAR devices." ([24], p. 478).

As a result, the author concluded one Navtech DS2000 was in use by Teams 2005-13 and 2005-14, and considers this sensor known.

V.C.38.c. Unknown other sensors

Teams 2005-13 and 2005-14 stated: "In selecting sensors, the team evaluated monocular cameras, stereo cameras, LIDAR, and RADAR systems to find modalities amenable to generating terrain evaluations under the difficult conditions of the Grand

Challenge. Table I outlines the sensing modalities considered and the advantages and disadvantages for this problem." ([24], p. 476). Via Table 1 ("A qualitative comparison of sensors considered for inclusion in the navigation system.") of the Journal of Field Robotics ([24], p. 476), Teams 2005-13 and 2005-14 reported considering "conventional camera", "stereo camera", and "automotive RADAR" sensors in addition to LIDAR and "navigation RADAR".

However, Teams 2005-13 and 2005-14 also stated: "These considerations led to a perception strategy based on a set of five LIDAR and a navigation RADAR." ([24], p. 476).

The author concluded conventional camera, stereo camera, and automotive RADAR sensors were not in use by Teams 2005-13 and 2005-14.

V.C.38.d. Unknown Applanix INS

Teams 2005-13 and 2005-14 stated: "The INS/GPS (Applanix POS LV) is a strapdown inertial navigation platform..." ([11], p. 7 and [12], p. 7), but reported no additional identifying information.

Teams 2005-13 and 2005-14 later stated: "The Applanix M-POS provides position estimates..." ([24], p. 478). A search of the manufacturer website ([187]) for a product with model number "m-pos" did not produce any results. An Internet search using the key words "+applanix +'m-pos'" as the search string produced three results, two of which were references to the Journal of Field Robotics ([24]), and the third so similarly-worded as to suggest its source was the Journal of Field Robotics ([24]).

Several model numbers of the POS LV exist: 200, 220, 420, and 610 ([120]). At least two of these model numbers were available at the time of the 2005 GCE: 220 and 420 ([124]), and the author concluded 320 was an existing model number at the time of the 2004 GCE based on review of manufacturer product literature. See paragraph V.C.8.d.

Alternate sources variously stated: "Around the same time as vehicle designs were being drafted and redesigned..., a meeting between [Team 2005-13] and Applanix over the capabilities of POS LV technology quickly developed into a strong partnership." ([188], p. 71) and "[Team 2005-13] engineers immediately recognized the value of having data from the GPS, IMU and DMI blended together in real time and began working to include the POS LV system on both Red Team vehicles." ([188], p. 72); and "Risk adverse [*sic*] [Team 2005-13] engineers adopted a system approach with redundancy and back-ups for both [Team 2005-13] vehicles. ... Applanix POS LV technology with inertial/GPS and distance measurement hardware generated position and orientation data throughout the course." ([189], p. 43) and "[Team 2005-13] engineers adopted the Applanix POS LV system." ([189], p. 44).

The author concluded one Applanix INS was in use by Teams 2005-13 and 2005-14, but considers the model number of this sensor unknown.

V.C.38.e. Trimble AgGPS 252

Team 2005-13 stated: “A differential GPS receiver (Trimble AG132 with Omnistar VBS corrections) augments the INS/GPS’s two antennas to enhance position estimation.” ([11], p. 7). Team 2005-14 stated: “A differential GPS receiver (Trimble AG252 with Omnistar VBS corrections) augments the INS/GPS’s two antennas to enhance position estimation.” ([12], p. 7).

Teams 2005-13 and 2005-14 did not refer to “Trimble” throughout the Journal of Field Robotics ([24]), and references to “GPS” reported no additional identifying information.

Alternate sources stated: “The only addition to this system setup for [Team 2005-13] at the 2005 DARPA Grand Challenge was a Trimble Ag 252 receiver which provided OmniSTAR VBS corrections for position information.” ([190], p. 1237) and “The only addition to this system setup for [Team 2005-13] was a Trimble Ag 252 receiver which provided RTCM corrections for position information.” ([191], p. 373). Although only the Team 2005-13 name is used by both alternate sources ([190] and [191]), it is used to describe both Team 2005-13 and 2005-14 challenge vehicles.

Trimble does not manufacture an “Ag 252” DGPS receiver ([192]); the corresponding model number is “AgGPS 252”. The author concluded it was likely this was an error and that one Trimble AgGPS 252 was in use by Teams 2005-13 and 2005-14, and considers this sensor known.

V.C.39. Team 2005-15

- Team 2005-15 participated in the 2004 QID and GCE as Team 2004-13. See paragraph V.C.13.
- The Team 2005-15 website was no longer available.

V.C.39.a. Unknown SICK LIDAR sensors

Team 2005-15 stated: “The main obstacle sensing is based on SICK LIDAR sensors. Two of these sensors are used to scan horizontally, to detect objects that are in the path to be driven. Two other LIDAR sensors scan vertically, to detect surface continuity and discontinuity (negative obstacles).” ([53], p. 9), but reported no additional identifying information.

Team 2005-15 later stated: “Five sensors were used to search for obstacles within the corridor: The stereo vision system (SVS) from Seibersdorf Research and four SICK

LMS-221 light detection and ranging device (LIDAR) units...” ([133], p. 586), but did not report the model number of the SICK LIDAR sensors in use by the team.

The author concluded four SICK LIDAR sensors were in use by Team 2005-15, but considers the model number of these sensors unknown.

V.C.39.b. Team 2005-15 stereo camera pair

Team 2005-15 stated: “As a mid-range (10 m < R <20m) obstacle sensing system, a stereo vision system jointly developed by Seibersdorf research and [Advanced Computer Vision], is used.” ([53], p. 9). Team 2005-15 later referred to this sensor as a “novel stereo vision system” ([133], p. 579).

Although the Team 2005-15 description of this sensor was detailed, the author was unable to determine if this was a proprietary stereo camera pair or a commercially-available product similar to other commercially-available stereo camera pairs in use by teams participating in the 2005 GCE. Considering its description as “novel”, the author concluded it was unlikely the stereo camera pair was a commercially-available product at the time of the 2005 GCE.

The author considers the stereo camera pair in use by Team 2005-15 known, but concluded the cost of this sensor cannot be independently determined.

V.C.39.c. Unknown ultrasonic sensors and unknown contact sensors

Team 2005-15 stated: “Other sensors include a suite of ultrasound sensors...” ([53], p. 9), but reported no additional identifying information.

Team 2005-15 later stated: “Further work was planned to integrate ultrasonic and contact sensors to discriminate between false and real obstacles, but was not implemented.” ([133], p. 591). Team 2005-15 did not refer to “contact” sensors throughout the team technical paper ([53]).

The author concluded the unknown ultrasonic sensors and unknown contact sensors were not in use by Team 2005-15.

V.C.39.d. Unknown NavCom DGPS receiver

Team 2005-15 stated: “The primary sensor used in estimating vehicle state is a Navcom Starfire GPS system...” ([53], p. 9), but reported no additional identifying information.

Team 2005-15 later stated: “The cornerstone of vehicle localization was a single antenna Navcom differential global positioning system (DGPS) receiver with Starfire corrections broadcast by Navcom.” ([133], p. 582), but reported no additional identifying information.

The NavCom StarFire SF-2050 GPS receiver and StarFire network were in use by 12 of 40 NQE semifinalists ([102]) and 6 of 23 GCE finalists ([103]). At least two different model numbers of NavCom StarFire GPS receiver existed at the time of the 2005 GCE, and they targeted different markets: "The SF-2050G is designed for backpack GIS and mapping applications while the SF-2050M is ideal for vehicle mounting to suit a wide variety of machine guidance and control applications." ([104]). NavCom launched both the SF-2050G or SF-2050M receivers in 2002 ([105]). Although the SF-2050M was specifically designed to be vehicle-mounted, review of technical papers revealed both sensors were in use by teams participating in the 2004 and 2005 GCE, and that the SF-2050G was more popular[22].

The author concluded one NavCom DGPS receiver was in use by Team 2005-15, but considers the model number of this sensor unknown.

V.C.39.e. Unknown Rockwell Collins IMU

Team 2005-15 stated: "A Rockwell Collins GNP-10 provides inertial updates of acceleration and angular rate at 50 Hz through accelerometers and gyros." ([53], p. 9).

Team 2005-15 later stated: "An inertial measurement unit (IMU) was used to obtain high update rate measurements. A Rockwell Collins GIC-100 tactical-grade six degrees of freedom IMU measured translational accelerations and angular rates at 50 Hz." ([133], p. 582).

The author was unable to confirm that "GIC-100" was an existing product at the time of the 2005 GCE. A search of the Rockwell Collins Product Catalog ([193]) and Technical Publications Index ([194]) for "gic", "gic-100", and the potential variant "g1c" did not produce any results. An Internet search using the key words "+'rockwell collins' +'gic-100'" as the search string produced 16 results, several of which were so similarly-worded as to suggest their source was the Journal of Field Robotics ([133]).

Based on a review of the published record, the author concluded it was possible that Rockwell Collins produced a model number GIC-100 IMU at the time of the 2005 GCE that may not have been commercially available, or that it has since been discontinued. In the absence of evidence that a GIC-100 IMU was in use by Team 2005-15 during the 2005 GCE, the author concluded one Rockwell Collins IMU was in use by Team 2005-15, but considers the model number of this sensor unknown.

V.C.39.f. PNI TCM2 magnetometer

Team 2005-15 stated: "A TCM2 magnetometer provides roll, pitch, and yaw data at 16 Hz." ([53], p. 9), but did not identify the manufacturer of this sensor.

Team 2005-15 later stated: “A TCM2 magnetometer provided 16 Hz measurements that contained high noise, but a slow bias drift rate.” ([133], p. 582), but did not identify the manufacturer of this sensor.

The TCM2 magnetometer is a product of PNI. The author concluded one PNI TCM2 magnetometer was in use by Team 2005-15, and considers this sensor known.

V.C.39.g. OEM speedometer encoder

Team 2005-15 stated: “A speedometer encoder provides speed data at a variable rate, depending on the speed of the vehicle.” ([53], p. 9), but reported no additional information.

Team 2005-15 later stated: “[The challenge vehicle's] onboard speedometer was used as an additional speed sensor.” ([133], p. 582).

The author concluded the challenge vehicle's OEM speedometer was in use by Team 2005-15 as a “speedometer encoder”, and considers this sensor known.

V.C.40. Team 2005-16

- The Team 2005-16 website reported no additional identifying information for the sensors in use by the team.

V.C.40.a. Unknown GPS receiver and unknown GPS compass

Team 2005-16 stated: “A number of antenna are also attached to the roof rack, specifically one antenna for the GPS positioning system, two additional GPS antennae for the GPS compass... Three additional GPS antenna [*sic*] for the DARPA E-Stop are directly attached to the roof.” ([195], p. 4), but reported no additional identifying information.

Although Team 2005-16 specifically referred to six GPS antennas throughout the team technical paper ([195]), three are of particular interest because they are used by the “GPS positioning system” and “GPS compass”. Team 2005-16 later stated: “The GPS positioning unit is a L1/L2/Omnistar HP receiver.” ([25], p. 665). “L1”, “L2”, and “Omnistar HP” are references to the specific types of GPS signals which are common to many commercially-available DGPS receivers.

As a result, the author concluded one GPS receiver and one GPS compass were in use by Team 2005-16, but otherwise considers these sensors unknown.

V.C.40.b. Unknown IMU

Team 2005-16 stated: “A 6 degree of freedom (DOF) inertial measurement unit (IMU) is rigidly attached to the vehicle frame underneath the computing rack in the trunk.” ([195], p. 5), but reported no additional identifying information.

Team 2005-16 later stated: “A six degree-of-freedom IMU is rigidly attached to the vehicle frame underneath the computing rack in the trunk.” ([25], p. 665), but reported no additional identifying information.

The author concluded one IMU was in use by Team 2005-16, but otherwise considers this sensor unknown.

V.C.40.c. Unknown SICK LIDAR sensors

Team 2005-16 stated: “For environment perception, the roof rack holds five SICK laser range finders...” ([195], p. 4), but reported no additional identifying information.

Team 2005-16 later stated: “For environment perception, the roof rack houses five SICK laser range finders.” ([25], p. 664), but reported no additional identifying information.

Team 2005-16 published a picture of the challenge vehicle's roof rack with sensors via the Journal of Field Robotics ([25]). The LIDAR sensors in use by Team 2005-16 appear to be SICK LMS 291 product family LIDAR sensors. However, in the absence of an affirmative statement by Team 2005-16 specifically identifying the model number of the SICK LIDAR sensors in use by the team, the author concluded five SICK LIDAR sensors were in use by Team 2005-16, but considers the model number of these sensors unknown.

V.C.40.d. Unknown camera

Team 2005-16 stated: “For environment perception, the roof rack holds ... a color camera...” ([195], p. 4), but reported no additional identifying information.

Team 2005-16 later stated: “The roof rack also holds a color camera for long-range road perception...” ([25], p. 664), but reported no additional identifying information. As noted above, the team published a picture of the challenge vehicle's roof rack with sensors via the Journal of Field Robotics ([25]). However, the author was unable to identify the camera, or determine the manufacturer and model number from the picture alone, and concluded one camera was in use by Team 2005-16, but otherwise considers this sensor unknown.

V.C.40.e. Unknown Smart Microwave RADARs

Team 2005-16 stated: “For environment perception, the roof rack holds ... two antennae of a forward-pointed RADAR system.” ([195], p. 4), but reported no additional identifying information.

Team 2005-16 later alternately stated: “[The challenge vehicle's] roof rack also holds two 24 GHz RADAR sensors, supplied by Smart Microwave Sensors.” ([25], p. 664), but reported no additional identifying information; and “The second sensor that was not used in the race was the 24 GHz RADAR system.” ([25], p. 686). The author concluded the Smart Microwave RADARs were not in use by Team 2005-16 during the 2005 GCE.

V.C.41. Team 2005-17

- Team 2005-17 participated in the 2004 QID and GCE as Team 2004-16. See paragraph V.C.16.
- The Team 2005-17 website reported no additional identifying information for the sensors in use by the team.

V.C.41.a. Unknown SICK LIDAR sensors

Team 2005-17 stated: “The single (functional) SICK LMS 221 is augmented by four SICK LMS 291s.” ([140], p. 2), “Four SICK LMS 291 LIDARs and one SICK LMS 221 constitute [the challenge vehicle's] obstacle sensors.” ([140], p. 5), and “The five SICK LMS configuration is the maximal configuration.” ([140], p. 5), but reported no additional identifying information.

Team 2005-17 later stated: “[The challenge vehicle] uses … two lidar scanners (SICK LMS 291) for autonomous operation.” ([196], p. 559). Team 2005-17 also stated: “...a SICK LMS 291 lidar operates at 75 Hz, producing scans separated by 13 ms intervals.” ([196], p. 567). These capabilities match the description of both the SICK LMS 291-S05 and 291-S15. Team 2005-17 did not report sufficient identifying information to determine which model was in use by the team.

The author concluded two SICK LIDAR sensors were in use by Team 2005-17 during the 2005 GCE, but considers the model number of these sensors unknown.

V.C.41.b. Oxford RT3102

Team 2005-17 stated: “An Oxford Technical Solutions RT3000 inertial navigation system (INS) is the primary navigation sensor.” ([140], p. 5).

Team 2005-17 later stated: “[The challenge vehicle] uses an inertial navigation system (INS) (Oxford Technology Solutions RT3102) ... for autonomous operation.” ([196], p. 559).

Because the Journal of Field Robotics ([196]) represents the final technical report of Team 2005-17, the author concluded one Oxford RT3102 was in use by Team 2005-17, and considers this sensor known.

V.C.41.c. Unknown C&C Technologies C-Nav DGPS receiver

Team 2005-17 stated: “The accuracy of the INS is enhanced by Starfire differential GPS correction signals provided by a C&C Technologies C-Nav receiver.” ([140], p. 5).

Several model numbers existed for the C&C Technologies C-Nav at the time of the 2005 GCE ([141]). The author concluded one C&C Technologies C-Nav DGPS receiver was in use by Team 2005-17, but considers the model number of this sensor unknown.

V.C.42. Team 2005-18

- Team 2005-18 participated in the 2004 QID and GCE as Team 2004-17. See paragraph V.C.17.
- The Team 2005-18 website was updated prior to the 2007 Urban Challenge, and reported no additional identifying information for the sensors in use by the team.

V.C.42.a. SICK LMS 221-30206, SICK LMS 291-S14, and SICK LMS 291-S05 LIDAR sensors

Team 2005-18 stated: “We currently have 2 SICK LMS-221-30206 LADARs mounted on [the challenge vehicle].” and “An additional SICK LMS 291-S14 LADAR has been mounted on the roof.” ([197], p. 10).

Team 2005-18 later stated: “Obstacle detection is performed using a combination of several SICK and Riegl LADAR units, as well as two pairs of stereovision cameras.” ([54], p. 789). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported that a SICK LMS 291-S05 LIDAR sensor was in use by the team, in addition to the three LIDAR sensors referred to previously.

The author concluded two SICK LMS 221-30206 LIDAR sensors, one SICK LMS 291-S14, and one SICK LMS 291-S05 were in use by Team 2005-18 and considers these sensors known.

V.C.42.b. Point Grey Dragonfly stereo camera pairs

Team 2005-18 stated: “A pair of Point Grey Dragonfly cameras mounted on the roof are used in combination with SRI’s Small Vision System to generate 3D pointclouds.” ([197], p. 10).

Team 2005-18 later stated: “Obstacle detection is performed using a combination of several SICK and Riegl LADAR units, as well as two pairs of stereovision cameras.” ([54], p. 789). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported two Point Grey Dragonfly “Stereovision” pairs were in use by the team.

Point Grey Research has product lines named “Bumblebee”, “Dragonfly”, “Flea”, etc. ([108]). Each product line has multiple model numbers. For example, the current model number for the Dragonfly product line is “Dragonfly 2” ([143]). The Dragonfly 2 was introduced January 20, 2005 ([144]). The Dragonfly is not available as a stereo camera pair ([146]).

The author concluded “Dragonfly” was the model number at the time of the 2005 GCE and that each stereo camera pair was comprised of two Point Grey Dragonfly cameras, and considers these sensors known.

V.C.42.c. Point Grey Dragonfly camera

Team 2005-18 stated: “An additional single camera mounted on the vehicle also feeds a road-finding algorithm.” ([197], p. 10).

Team 2005-18 later stated: “[The challenge vehicle's] road-following algorithm ... uses a single calibrated grayscale camera and a bumper-mounted SICK LADAR.” ([54], p. 793). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported one Point Grey Dragonfly “Road-finding camera” was in use by the team.

The author concluded the “additional single camera” referred to by the team technical paper ([197]) was the Point Grey Dragonfly in use by Team 2005-18 as a “Road-finding camera” during the 2005 GCE and considers this sensor known.

V.C.42.d. NovAtel DL-4plus and NavCom SF-2050G

Team 2005-18 stated: “State estimation is accomplished through the combination of Navcom SF2050G and Novatel ProPak-LBplus differential GPS units to measure absolute position...” ([197], p. 9). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 later reported that a “Navcom SF-2050” and “NovAtel DL-4plus” were in use by the team.

The author concluded one NovAtel DL-4plus, in lieu of the NovAtel ProPak-LBplus reported by the team technical paper ([197]), was in use by Team 2005-18 during the 2005 GCE, and considers this sensor known. In the absence of conflicting evidence that an alternate model number NavCom GPS receiver was in use by Team 2005-18, the author concluded one NavCom SF-2050G was in use by Team 2005-18, and considers this sensor known.

V.C.43. Team 2005-19

V.C.43.a. Unknown SICK LIDAR sensors

Team 2005-19 reported "two rigidly-mounted SICK LMS-291 LIDAR" and a "third LIDAR unit" were in use by the team ([55], p. 5), but did not report the model number of the SICK LIDAR sensors in use by the team. Figure 2 of the team technical paper ([55], p. 5) reported the third LIDAR sensor was also a SICK LIDAR sensor.

Team 2005-19 later stated: "Sensed terrain data for the terrain estimator is provided by three SICK LMS 291 laser rangefinders (LIDARs)." ([198], p. 636), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

The author concluded three SICK LIDAR sensors were in use by Team 2005-19, but considers the model number of these sensors unknown.

V.C.43.b. Basler A311FC stereo camera pair

Team 2005-19 stated: "...[Team 2005-19] also uses a pair of cameras to create a depth map of the surrounding world using stereo vision. The [Team 2005-19] stereo vision camera pair is a pair of Basler A311FC cameras..." ([55], p. 6).

However, Team 2005-19 did not refer to "stereo", "vision", "camera", or "Basler" throughout the Journal of Field Robotics ([198]). Because the Journal of Field Robotics ([198]) represents the final technical report of Team 2005-19, the author concluded the Basler A311FC stereo camera pair was not in use by Team 2005-19 during the 2005 GCE.

V.C.43.c. Northrop Grumman LN-200

Team 2005-19 reported a "a Litton LN-200 Inertial Measurement Unit (IMU)" was in use by the team ([55], p. 4).

Team 2005-19 later stated: "[The challenge vehicle's] fused position and orientation estimates are provided by three sensors: a Litton LN-200 IMU, a Trimble Ag252 GPS receiver, and a vehicle speed sensor." ([198], p. 629).

Litton was acquired by Northrop Grumman in 2001 ([199]). The LN-200 is a product of Northrop Grumman ([200]). The author concluded one Northrop Grumman LN-200 was in use by Team 2005-19, and considers this sensor known.

V.C.43.d. Trimble AgGPS 252

Team 2005-19 reported a “Trimble Ag252 GPS unit” was in use by the team ([55], p. 4).

Team 2005-19 later stated: “[The challenge vehicle's] fused position and orientation estimates are provided by three sensors: a Litton LN-200 IMU, a Trimble Ag252 GPS receiver, and a vehicle speed sensor.” and “The second sensor, a Trimble AgGPS 252 GPS receiver...” ([198], p. 629).

Trimble does not manufacture an “Ag 252” GPS receiver ([192]); the corresponding model number is “AgGPS 252”. The author concluded this was an error and that one Trimble AgGPS 252 was in use by Team 2005-19, and considers this sensor known.

V.C.43.e. Unknown speed brake sensor

Team 2005-19 reported a “speed brake sensor (SBS)” was in use by the team ([55], p. 4). Team 2005-19 later stated: “[The challenge vehicle's] fused position and orientation estimates are provided by three sensors: a Litton LN-200 IMU, a Trimble Ag252 GPS receiver, and a vehicle speed sensor.” and “The final sensor, a speed sensor (SBS), is mounted directly to [the challenge vehicle's] transmission.” ([198], p. 629), but reported no additional identifying information.

The author concluded one “speed brake sensor” was in use by Team 2005-19, but otherwise considers this sensor unknown.

V.C.44. Team 2005-20

- Team 2005-20 participated in the 2004 QID and GCE as Team 2004-18. See paragraph V.C.18.
- Team 2005-20 did not publish its results via the Journal of Field Robotics.
- The hyperlink to the Team 2005-20 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to another website, which was updated prior to the 2007 Urban Challenge, but reported no additional identifying information for the sensors in use by Team 2005-20.

Team 2005-20 stated: “Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems.” ([56], p. 2).

V.C.44.a. Unknown LIDAR sensor(s)

Team 2005-20 did not report any identifying information for the "LIDAR ... systems" in use by the team. The author considers these sensors unknown.

V.C.44.b. Unknown RADAR(s)

Team 2005-20 did not report any identifying information for the "Millimeter Wave Radar ... systems" in use by the team. The author considers these sensors unknown.

V.C.44.c. Unknown stereo camera pair(s)

Team 2005-20 did not report any identifying information for the "Stereo Vision Camera ... systems" in use by the team. The author considers these sensors unknown.

V.C.44.d. NovAtel ProPak-LBplus and NovAtel HG1700 SPAN

Team 2005-20 stated: "[Team 2005-20] has developed a system that combines two Novatel Pro-Pack LB dual frequency (L1/L2) GPS receivers and NovAtel's SPAN™ (Synchronized Position Attitude Navigation) Technology." ([56], pp. 8 - 9). NovAtel's SPAN is available for several different IMUs ([201]). Team 2005-20 also stated: "...the SPAN system provides location information at a 20-Hz rate by combining DGPS and inertial data from an internal Honeywell HG-1700 tactical-grade IMU." ([56], p. 9).

The author concluded two NovAtel ProPak-LBplus[21] and one NovAtel HG1700 SPAN were in use by Team 2005-20, and considers these sensors known.

V.C.45. Team 2005-21

- Team 2005-21 participated in the 2004 QID and GCE as Team 2004-23. See paragraph V.C.23.

- The Team 2005-21 website reported no additional identifying information for the sensors in use by the team.

V.C.45.a. Unknown SICK LIDAR sensors

Team 2005-21 stated: "LIDAR and vision sensors are used to detect obstacles in front and behind the vehicle." ([160], p. 7) and "There are three SICK LMS-291 LIDARs used for positive and negative obstacle detection. The two forward facing SICK LIDARs are mounted on the outermost edges of the front rollbar. … The rear facing LIDAR is mounted near the cargo bed height in the middle of the truck..." ([160], p. 10), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

Team 2005-21 later stated: "There are two SICK LMS-291 LIDARs used for positive and negative obstacle detection..." ([57], p. 701), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

Although Team 2005-21 stated: "Obstacle detected behind the vehicle while backing up: Another behavior will stop the vehicle and command it back into normal operation to try to find a valid path ahead." ([57], p. 700), it is unclear what sensors were in use to detect obstacles behind the vehicle. The rear-facing SICK LIDAR sensor described by the team technical paper ([160]) was not reported to have been in use by the team via the Journal of Field Robotics ([57]).

As a result, the author concluded no rear-facing SICK LIDAR sensor was in use by Team 2005-21 during the 2005 GCE and that two SICK LIDAR sensors were in use by Team 2005-21, but considers the model number of these sensors unknown.

V.C.45.b. <u>Unknown Ibeo LIDAR sensor</u>

Team 2005-21 stated: "The IBEO ALASCA LIDAR is a 4-plane scanner that is used for positive obstacle detection." ([160], p. 10). However, Team 2005-21 did not report the model number of the IBEO LIDAR sensor in use by the team. The Journal of Field Robotics ([57]) confirms this sensor was in use by Team 2005-21 during the 2005 GCE.

The current version of the Ibeo ALASCA LIDAR is model number XT, and that it is offered in two different product lines: "Single", which includes one ALASCA XT sensor and "Fusion", which includes two ALASCA XT sensors ([202]). However, Ibeo stated: "In the form of Alasca XT, [Ibeo] has been presenting the first Multi-Application Sensor with high-resolution laser technology since October 2005." ([203]). The 2005 GCE took place on October 8, 2005. See Appendix C, paragraph I.B.11. As a result, the ALASCA XT could not have been the sensor in use by Team 2005-21 during the 2005 GCE.

An Ibeo "Case Study" stated: "...[Team 2005-21] opted for an innovative laser technology from Germany, the laser scanner developed and produced by [Ibeo]." ([204], p. 1). Throughout this "Case Study", Ibeo referred to "innovative", "historic", or "multi-application" LIDAR sensors ([204]), and also stated: "Ibeo developed the multi-application sensor ibeo XS especially for use in trucks and buses." without stating the "ibeo XS" sensor was in use by Team 2005-21 during the 2005 GCE. In addition, neither a search of the Ibeo website ([202]) for a sensor with model number "XS" nor an Internet search using the key words "'ibeo XS'" or "+ibeo +lidar +xs" as the search string produced any results for an Ibeo model number "XS" LIDAR sensor.

Team 2005-21 also participated in the 2007 Urban Challenge. The team website was updated to reflect the challenge vehicle configuration in use during that event, and stated: “Ibeo Automobile Sensor GmbH is providing a customized LIDAR system utilizing Ibeo's Alasca XT™ sensors.” ([205]).

As a result, the author concluded one Ibeo LIDAR sensor was in use by Team 2005-21, but considers the model number of this sensor unknown.

V.C.45.c. Unknown cameras

Team 2005-21 stated: “The vision system is comprised of a forward-looking system and a backward looking one. Both systems share the same technology and processing: color cameras and stereoscopic vision.”, and “The forward-looking system consists of three identical cameras mounted on a rigid bar on top of the hood.” ([160], p. 10). Team 2005-21 did not report any technical detail for the backward-looking vision system, or additional identifying information for the cameras in use by the team.

Team 2005-21 published its 2005 GCE results via the Journal of Field Robotics ([57]). The description of the challenge vehicle generally conforms to the description reported by the team technical paper ([160]), although Team 2005-21 referred to the “Parma Vision System” via the team technical paper ([160]) and the “forward-looking vision and [*sic*] system” via the Journal of Field Robotics ([57], p. 701). Team 2005-21 reported no additional identifying information for the cameras in use by the team.

Although Team 2005-21 stated: “Obstacle detected behind the vehicle while backing up: Another behavior will stop the vehicle and command it back into normal operation to try to find a valid path ahead.” ([57], p. 700), it is unclear what sensors were in use to detect obstacles behind the vehicle. The backward-looking vision system described by the team technical paper ([160]) was not described by the Journal of Field Robotics ([57]).

The trinocular camera system described by Team 2005-21 uses three identical cameras to form three stereo camera pairs with three different field-of-view depths: large, medium, and short.

As a result, the author concluded the backward-looking vision system was not in use by Team 2005-21 during the 2005 GCE and that three cameras were in use by Team 2005-21 in the forward-looking system, but otherwise considers these sensors unknown.

V.C.45.d. Unknown wheel speed sensor and wheel angle sensor

Team 2005-21 stated: “In order to aid the INS solution in dead reckoning mode, a wheel speed sensor on the vehicle provides input to the RT3100.” and “In the case of a failure or short-term loss of the RT3100’s, a second dead reckoner is implemented using sensed wheel speed and wheel angle.” ([160], p. 8), but reported no additional identifying information.

Team 2005-21 later stated: “The servomotor has an integrated high-resolution encoder that allows precise control of wheel angle.” ([57], p. 695) and “In the case of a failure or short-term loss of the RT3100’s, a second dead reckoner is implemented using sensed wheel speed and wheel angle.” ([57], p. 701), but reported no additional identifying information.

The author concluded one wheel speed sensor and one wheel angle sensor were in use by Team 2005-21, but otherwise considers these sensors unknown.

V.C.46. Teams 2005-22 and 2005-23

- Team 2005-22 participated in the 2004 QID and GCE as Team 2004-25. See paragraph V.C.25.
- Teams 2005-22 and 2005-23 were co-participants during the 2005 GCE, and published their results jointly via the Journal of Field Robotics ([59]).
- The Teams 2005-22 and 2005-23 website reported no additional identifying information for the sensors in use by the team.

V.C.46.a. <u>Unknown SICK LIDAR sensors</u>

Team 2005-22 stated: “The horizontally mounted scanning LIDAR scans a 180 degree arc in front of the vehicle and is hard-mounted in position. This sensor is used for primary obstacle detection. The advertised range of the LMS-291 is 80m, but [the challenge vehicle's] software only uses LIDAR data at a maximum range of 40m.” ([58], p. 6). Team 2005-22 did not report the model number of the SICK LMS 291 sensor in use by the team.

Team 2005-23 stated: “[The challenge vehicle] uses three scanning LIDAR...”, “Two Sick single plane scanning LIDAR are mounted to the top left and right front corners of the vehicle...”, and “The third LIDAR is an IBEO ALASCA...” ([164], p. 7).

Team 2005-23 did not report the model number of the SICK LIDAR sensors in use by the team. Although the Journal of Field Robotics ([59]) confirmed the quantity of SICK LIDAR sensors in use by Teams 2005-22 and 2005-23, it contradicted the Team 2005-23 technical paper ([164]) by stating that a third SICK LIDAR sensor was in use by Team 2005-23 in lieu of an IBEO LIDAR sensor, and reported no additional identifying information for the LIDAR sensors in use by Teams 2005-22 and 2005-23.

The author concluded one SICK LIDAR sensor was in use by Team 2005-22 during the 2005 GCE, but considers the model number of this sensor unknown. The author concluded the IBEO LIDAR sensor was not in use by Team 2005-23 and that three SICK LIDAR sensors were in use by Team 2005-23 during the 2005 GCE, but considers the model number of these sensors unknown.

V.C.46.b. NovAtel ProPak-LBplus and NovAtel HG1700 SPAN

Team 2005-22 stated: "[The challenge vehicle] uses a Honeywell TALIN inertial navigation system coupled with a Rockwell-Collins PLGR GPS to determine position, velocity and attitude." ([58], p. 6).

Teams 2005-22 and 2005-23 later stated: "Both vehicles used Novatel Propak LBplus positioning systems ... in the Grand Challenge... The system consists of a Novatel Propak LBplus GPS receiver and a Novatel IMUG2 enclosure housing a Honeywell HG1700 inertial measurement unit (IMU)." ([59], p. 711).

NovAtel stated: "The ProPak-LB plus features NovAtel's SPAN™ Technology to provide support for an external inertial measurement unit (IMU)." ([206]). The author concluded it was likely the Honeywell HG1700 IMU referred to by the Journal of Field Robotics ([59]) was actually a NovAtel HG1700 SPAN (see also paragraph V.C.44.d.).

The author concluded one NovAtel ProPak-LBplus[21] and one NovAtel HG1700 SPAN were in use by Team 2005-22 during the 2005 GCE, in lieu of the Honeywell TALIN INS and Rockwell-Collins PLGR GPS reported by the Team 2005-22 technical paper ([58]), and considers these sensors known.

The author concluded one NovAtel ProPak-LBplus[21] and one NovAtel HG1700 SPAN were in use by Team 2005-23 during the 2005 GCE, and considers these sensors known.

V.C.46.c. Point Grey Bumblebee stereo camera pair

Via Figure 1 of the team technical papers ([58], p. 4 and [164], p. 4), Teams 2005-22 and 2005-23 reported one Point Grey Bumblebee stereo camera pair was in use by the teams. Team 2005-22 stated: "If a road is detected by the stereo vision cameras..." ([58], p. 8), but otherwise referred to a "stereo vision camera" or "camera" throughout the Team 2005-22 technical paper ([58]). Team 2005-23 referred to a "stereo vision camera" or "camera" throughout the Team 2005-23 technical paper ([164]).

Teams 2005-22 and 2005-23 later stated: "A Point Grey Bumblebee stereovision camera, mounted to the top center of the vehicle's roll cage, is used to observe the area in front of the vehicle." ([59], p. 712). The author concluded it was likely the Team 2005-22 reference to "cameras" was an error, and that one stereo camera pair was in use by the team.

In addition, Teams 2005-22 and 2005-23 later stated: "The monocular/stereovision system allows [the challenge vehicles] to perceive roads ahead of the vehicle and mark them as preferred areas of travel." ([59], p. 712), but later reported the "monocular system" described referred to the use of stereo vision camera images for road detection: "After simplifying the image, the software searches for the basic geometric characteristics that define a road. This search is done using only one of the 2D images provided by the stereocameras." ([59], p. 712). The author concluded no additional camera was in use by either Team 2005-22 or 2005-23 during the 2005 GCE.

The author concluded one Point Grey Bumblebee stereo camera pair was in use by Teams 2005-22 and 2005-23, and considers this sensor known.

V.C.46.d. Unknown encoders

Via Figure 1 of the team technical papers ([58], p. 4 and [164], p. 4), Teams 2005-22 and 2005-23 reported "Encoders" were in use by the teams, but reported no additional identifying information.

Teams 2005-22 and 2005-23 later stated: "Both vehicles actuate the throttle using a dc gear motor with integrated encoder feedback." and "Both vehicles use right-angle gear motors fitted with quadrature encoders to actuate the steering." ([59], p. 710), but reported no additional identifying information.

The author concluded one "throttle" encoder and one "steering" encoder were in use by Teams 2005-22 and 2005-23, but otherwise considers these sensors unknown.

V.D. Results

Results for 2004 technical papers are presented in Tables XXIX, XXX, and XXXI, and summarized in paragraph V.D.1. below. Results for 2005 technical papers are presented in Table XXXII, XXXIII, and XXXIV, and summarized in paragraph V.D.2. below. The columns "K", "U", and "E" represent "known", "unknown", and "estimated", respectively.

V.D.1. 2004

V.D.1.a. Known sensors by quantity (2004 QID and GCE participants)

See Table XXIX.

V.D.1.a.i. State sensors

The 25 2004 technical papers described 90 state sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 90 state sensors, 47 were in use by teams which participated in the 2004 GCE.

V.D.1.a.i.a. Known

- The quantity of 31 of 90 (34.4 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The quantity of 16 of 47 (34.0 percent) state sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.a.i.b. Unknown

- The quantity of 16 of 90 (17.8 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The quantity of nine of 47 (19.1 percent) state sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.a.i.c. Estimated

- The quantity of 43 of 90 (47.8 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were were estimated by the author in accordance with paragraph V.B.3.a.

- The quantity of 22 of 47 (46.8 percent) state sensors in use by teams which participated in the 2004 GCE were estimated by the author in accordance with paragraph V.B.3.a.

V.D.1.a.ii. Environment sensors

The 25 2004 technical papers describe 96 environment sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 96 environment sensors, 61 were in use by teams which participated in the 2004 GCE.

V.D.1.a.ii.a. Known

- The quantity of 81 of 96 (84.4 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The quantity of 50 of 61 (82.0 percent) environment sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.a.ii.b. Unknown

- The quantity of 11 of 96 (11.5 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The quantity of seven of 61 (11.5 percent) environment sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.a.ii.c. Estimated

- The quantity of four of 96 (4.2 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were estimated by the author as described in paragraph V.C.

- The quantity of four of 61 (6.6 percent) environment sensors in use by teams which participated in the 2004 GCE were estimated by the author as described in paragraph V.C.

V.D.1.a.iii. Navigation sensors

The 25 2004 technical papers describe 103 navigation sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 103 navigation sensors, 62 were in use by teams which participated in the 2004 GCE.

V.D.1.a.iii.a. Known

- The quantity of 89 of 103 (86.4 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The quantity of 52 of 62 (83.9 percent) navigation sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.a.iii.b. Unknown

- The quantity of four of 103 (3.9 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The quantity of one of 62 (1.6 percent) navigation sensors in use by teams which participated in the 2004 GCE was unknown.

V.D.1.a.iii.c. Estimated

- The quantity of ten of 103 (9.7 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were estimated by the author in accordance with paragraph V.B.5.c.

- The quantity of nine of 62 (14.5 percent) navigation sensors in use by teams which participated in the 2004 GCE were estimated by the author in accordance with paragraph V.B.5.c.

V.D.1.b. Known sensors by manufacturer (2004 QID and GCE participants)

See Table XXX.

V.D.1.b.i. State sensors

The 25 2004 technical papers describe 90 state sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 90 state sensors, 47 were in use by teams which participated in the 2004 GCE.

V.D.1.b.i.a. Known

- The manufacturers of 13 of 90 (14.4 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The manufacturers of nine of 47 (19.1 percent) state sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.b.i.b. Unknown

- The manufacturers of 77 of 90 (85.6 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The manufacturers of 38 of 47 (80.9 percent) state sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.b.ii. Environment sensors

The 25 2004 technical papers describe 96 environment sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 96 environment sensors, 61 were in use by teams which participated in the 2004 GCE.

V.D.1.b.ii.a. Known

- The manufacturers of 57 of 96 (59.4 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The manufacturers of 37 of 61 (60.7 percent) environment sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.b.ii.b. Unknown

- The manufacturers of 39 of 96 (40.6 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The manufacturers of 24 of 61 (39.3 percent) environment sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.b.iii. Navigation sensors

The 25 2004 technical papers describe 103 navigation sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 103 navigation sensors, 62 were in use by teams which participated in the 2004 GCE.

V.D.1.b.iii.a. Known

- The manufacturers of 58 of 103 (56.3 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were known.
- The manufacturers of 36 of 62 (58.1 percent) navigation sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.b.iii.b. Unknown

- The manufacturers of 45 of 103 (43.7 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were unknown.
- The manufacturers of 26 of 62 (41.9 percent) navigation sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.c. Known sensors by manufacturer and model number (2004 QID and GCE participants)

See Table XXXI.

V.D.1.c.i. State sensors

The 25 2004 technical papers describe 13 state sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers, some of which were common to more than one challenge vehicle. Of the 13 state sensors with known manufacturers, nine were in use by teams which participated in the 2004 GCE.

V.D.1.c.i.a. Known

- The model numbers of 12 of 13 (92.3 percent) state sensors with known manufacturers in use by teams which participated in both the 2004 QID and GCE were known.
- The model numbers of nine of nine (100.0 percent) state sensors with known manufacturers in use by teams which participated in the 2004 GCE were known.

V.D.1.c.i.b. Unknown

- The model numbers of one of 13 (7.7 percent) state sensors with known manufacturers in use by teams which participated in both the 2004 QID and GCE were unknown.

- No state sensors with known manufacturers in use by teams which participated in the 2004 GCE were unknown.

V.D.1.c.ii. Environment sensors

The 25 2004 technical papers describe 57 environment sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers, some of which were common to more than one challenge vehicle. Of the 57 environment sensors with known manufacturers, 37 were in use by teams which participated in the 2004 GCE.

V.D.1.c.ii.a. Known

- The model numbers of 33 of 57 (57.9 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were known.

- The model numbers of 17 of 37 (45.9 percent) environment sensors in use by teams which participated in the 2004 GCE with known manufacturers were known.

V.D.1.c.ii.b. Unknown

- The model numbers of 24 of 57 (42.1 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were unknown.

- The model numbers of 20 of 37 (54.1 percent) environment sensors in use by teams which participated in the 2004 GCE with known manufacturers were unknown.

V.D.1.c.iii. Navigation sensors

The 25 2004 technical papers describe 58 navigation sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers, some of which were common to more than one challenge vehicle. Of the 58 navigation sensors with known manufacturers, 36 were in use by teams which participated in the 2004 GCE.

V.D.1.c.iii.a. Known

- The model numbers of 38 of 58 (65.5 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were known.

- The model numbers of 24 of 36 (66.7 percent) navigation sensors in use by teams which participated in the 2004 GCE with known manufacturers were known.

V.D.1.c.iii.b. Unknown

- The model numbers of 20 of 58 (34.5 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were unknown.

- The model numbers of 12 of 36 (33.3 percent) navigation sensors in use by teams which participated in the 2004 GCE with known manufacturers were unknown.

V.D.2. 2005

V.D.2.a. Known sensors by quantity (2005 GCE participants)

See Table XXXII.

V.D.2.a.i. Environment sensors

The 23 2005 technical papers describe 66 environment sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.a.i.a. Known

The quantity of 60 of 66 (90.9 percent) were known.

V.D.2.a.i.b. Unknown

The quantity of six of 66 (9.1 percent) were unknown.

V.D.2.a.ii. Navigation sensors

The 23 2005 technical papers describe 70 navigation sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.a.ii.a. Known

The quantity of 67 of 70 (95.7 percent) were known.

V.D.2.a.ii.b. Unknown

The quantity of one of 70 (1.4 percent) was unknown.

V.D.2.a.ii.c. Estimated

The quantity of two of 70 (2.9 percent) were estimated by the author in accordance with paragraph V.B.5.c.

V.D.2.b. Known sensors by manufacturer (2005 GCE participants)

See Table XXXIII.

V.D.2.b.i. Environment sensors

The 23 2005 technical papers describe 66 environment sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.b.i.a. Known

The manufacturers of 52 of 66 (78.8 percent) were known.

V.D.2.b.i.b. Unknown

The manufacturers of 14 of 66 (21.2 percent) were unknown.

V.D.2.b.ii. Navigation sensors

The 23 2005 technical papers describe 70 navigation sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.b.ii.a. Known

The manufacturers of 51 of 70 (72.9 percent) were known.

V.D.2.b.ii.b. Unknown

The manufacturers of 19 of 70 (27.1 percent) were unknown.

V.D.2.c. Known sensors by manufacturer and model number (2005 GCE participants)

See Table XXXIV.

V.D.2.c.i. Environment sensors

The 23 2005 technical papers describe 52 environment sensors in use by teams which participated in the 2005 GCE with known manufacturers, some of which were common to more than one challenge vehicle.

V.D.2.c.i.a. Known

The model numbers of 31 of 52 (59.6 percent) were known.

V.D.2.c.i.b. Unknown

The model numbers of 21 of 52 (40.4 percent) were unknown.

V.D.2.c.ii. Navigation sensors

The 23 2005 technical papers describe 51 navigation sensors in use by teams which participated in the 2005 GCE with known manufacturers, some of which were common to more than one challenge vehicle.

V.D.2.c.ii.a. Known

The model numbers of 39 of 51 (76.5 percent) were known.

V.D.2.c.ii.b. Unknown

The model numbers of 12 of 51 (23.5 percent) were unknown.

V.D.3. Summary of results

The results of the comprehensive review of technical papers for teams which participated in both the 2004 QID and GCE and selected review of technical papers for teams which participated in the 2005 GCE are summarized by Table I. For each category reported by paragraph V.D., the known, unknown, and estimated sensors are represented as a percentage of the total quantity of sensors in use by the teams.

Table I. Results of the review of 2004 and 2005 technical papers.										
		Percentage of all sensors								
		2004 QID/GCE			2004 GCE			2005 GCE		
		K	U	E	K	U	E	K	U	E
State	Quantity	34.4	17.8	47.8	34.0	19.1	46.8			
	Manufacturer	14.4	85.6		19.1	80.9				
	Model No.	92.3	7.7		100					
Environment	Quantity	84.4	11.5	4.2	82.0	11.5	6.6	90.9	9.1	
	Manufacturer	59.4	40.6		60.7	39.3		78.8	21.2	
	Model No.	57.9	42.1		45.9	54.1		59.6	40.4	
Navigation	Quantity	86.4	3.9	9.7	83.9	1.6	14.5	95.7	1.4	2.9
	Manufacturer	56.3	43.7		58.1	41.9		72.9	27.1	
	Model No.	65.5	34.5		66.7	33.3		76.5	23.5	

V.D.3.a. Differences between 2004 QID and GCE results

The inclusion of teams which participated in the 2004 QID in the totals reported by Table I had no significant impact. The quantity of state sensors for which the manufacturer was unknown decreased from 85.6 to 80.9 percent (a decrease of 4.7 percent) when teams which participated in the 2004 QID were excluded, while the quantity of environment sensors for which both the manufacturer and model number was unknown increased from 42.1 to 54.1 (an increase of 12.0 percent). For the other 2004 totals reported, the difference was not considered significant.

V.D.3.b. Differences between 2004 and 2005 GCE results

The differences between 2004 and 2005 GCE results in each category reported by paragraph V.D. were significant. Not only was there an increase in the quantity of known sensors in each category, but there was an increase of 13.7 percent in the quantity of environment sensors with known manufacturers and model numbers, and 9.8 percent in the quantity of navigation sensors with known manufacturers and model numbers.

However, although 90.9 and 95.7 percent of the quantity of environment and navigation sensors, respectively, in use by the teams which participated in the 2005 GCE were known, the author was only able to determine the manufacturer and model number of 59.6 and 76.5 percent of the sensors, respectively.

V.E. Conclusion

Two of 48 teams reported sufficient technical detail via their 2004 or 2005 technical papers to determine the quantity, manufacturer, and model number for described state, environment, and navigation sensors: Teams 2004-17 and 2005-18. Team 2004-17 participated in the 2005 GCE as Team 2005-18.

As a result, the author concluded it would not be possible to reliably estimate the total cost of the sensor technology in use by each team using published records. Overall, attempting to determine the quantity, manufacturer, and model number for the various challenge vehicles' state, environment, and navigation sensors proved to be a time-consuming, tedious task requiring the author to very carefully review 2004 and 2005 technical papers for any information which might in any way provide some insight into the vehicles' sensor load, team websites for additional identifying information where possible, and other published records to determine if the vehicle described by the technical papers was actually the vehicle which participated in the 2004 and 2005 GCE.

V.E.1. Primary sources of uncertainty

V.E.1.a. <u>Technical paper requirements</u>

- 2004

DARPA established a requirement that teams participating in the 2004 QID or GCE submit a technical paper describing their challenge vehicle ([1]):

> A technical paper describing the Challenge Vehicle must be received at DARPA on or before the application deadline. A description of the mandatory subjects to be addressed in this paper is on the DARPA Grand Challenge web site (www.darpa.mil/grandchallenge).
>
> The technical paper will be reviewed by DARPA to ensure that the Challenge Vehicle design complies with the Rules. The panel also will judge the technical competence of the design and may not accept incomplete or ineffectual proposals.

The "description of the mandatory subjects to be addressed in this paper" was not available from the Archived Grand Challenge 2004 website ([17]).

DARPA also established a requirement that teams participating in the 2004 QID or GCE submit addenda to their technical papers if necessary ([1]):

> DARPA must be informed as soon as possible of any deviation in the technical approach described in a

current technical paper. These technical paper addenda may be submitted to DARPA without penalty prior to the application deadline or any time after the initial technical paper has been approved as long as they are submitted at least 14 calendar days prior to the QID in order that DARPA will have time to review and approve the deviation.

The technical paper addenda are intended for minor modifications and refinement of the Challenge Vehicle design. The addition or improvement of code, sensors, suspension, or actuators on basically the same vehicle, for example, are appropriate for a technical paper addendum.

DARPA later amended this requirement, and stated: “Addendums must be submitted as complete technical papers with the changes from the current technical paper marked. Alternately, these changes can be delineated in a separate document.” ([6]).

DARPA also established a requirement that technical papers and addenda submitted by teams participating in the 2004 GCE be reasonably accurate:

DARPA stated: “Challenge Vehicles presented for the Qualification Inspections and Demonstration (QID) that deviate substantially from the description in the approved technical paper (including approved addenda) will be disqualified.” ([1]). DARPA did not later amend this requirement.

DARPA later stated: “[The technical paper] is an integral part of the rules enforcement process that will help ensure this event is a fair and safe competition for all involved. Judges performing the technical inspection on the day prior to the main event will use the paper to validate the vehicles. Therefore, the paper should contain sufficient detail that a person could compare the vehicle to the paper and verify all the hardware that is present. As an example, 'the vehicle will use lidar' is not sufficiently detailed. If a commercial system is used, a reference to its specifications should be provided, as well as the planed [*sic*] location on the vehicle. If the system is completely home built, the components should be described in detail.” ([207]).

- 2005

DARPA established a similar requirement that teams participating in the 2005 GCE submit a technical paper describing their challenge vehicle ([2], p. 18):

A technical paper describing the vehicle of each semifinalist must be received at DARPA by August 15, 2005. A description of the subjects that must be addressed in the technical paper will be available on the Grand Challenge website.

Neither the 2005 GCE rules ([2]) nor the 2005 GCE Technical Paper Guidelines ([208]) require the submission of technical paper addenda if necessary.

V.E.1.b. Errors, omissions, and inconsistencies

During the review, it quickly became apparent that the technical papers submitted to DARPA were of indifferent quality, containing a large number of technical mistakes, and having generally poor presentation, such as figures which were missing or were shifted to later pages due to pagination problems or off of the page entirely, lack of whitespace, and errors of punctuation and pluralization which rendered meanings unclear, and that it would not be possible to reliably estimate the total cost of the sensor technology in use by each team based on their descriptions. The use of the words “the”, “a”, “an”, “was”, and “were” in combination with pluralization was often the only clue to the quantity of sensors in use. Examples have been noted throughout this technical report.

In addition, later published records directly contradict some technical papers, resulting in a difference between the proposed sensor load and reported sensor load. For this reason, and because of other differences between team technical papers and later published records, the phrase “technical proposal” is used in lieu of “technical paper” in all later chapters of this technical report. Although the author did not tabulate the proposed sensor load for each vehicle, it is of interest because a comparison between the proposed sensor load and the reported sensor load might identify sensors which were, in practice, more difficult to integrate than anticipated, or identify sensors the use of which was abandoned because they provided information of little utility.

V.E.1.c. Insufficient technical detail

Insufficient technical detail was the most significant contributing factor to an overall inability to determine the quantity, manufacturer, and model number of state, environment, and navigation sensors in use by the teams. Most commonly, a team failed to report the complete model number for the environment sensors in use by the team.

DARPA identified this as a weakness in correspondence with teams participating in the 2004 QID or GCE approximately six weeks before the teams were required to submit their technical paper. DARPA stated: “Common weak areas in technical paper submissions are a lack of completeness and a lack of detail.” ([207]). However, despite having established a requirement that teams participating in the 2004 QID or GCE describe their challenge vehicle in “sufficient detail” and identifying lack of detail as a problem, teams did not report sufficient technical detail to determine what sensors were in use by the team.

Several teams attempted to answer the questions DARPA asked in the format they were asked. For example, Team 2004-15 stated: “The following [Team 2004-15] technical information is presented in the same format as the Required Contents in the Technical Paper Requirements.” ([137], p. 1). The author was unable to locate a copy of the 2004 GCE “Technical Paper Requirements” for review, although a copy of the 2005 Technical Paper Guidelines ([208]) was hosted by DARPA via the Archived Grand Challenge 2005 website ([19]).

To a certain extent, the standard questions to which DARPA requested teams respond in their technical papers may have predetermined the content of some team's responses and had a negative impact on the overall quality of team technical papers.

Several of the standard questions were ambiguous. When the intent of the standard question was unclear, the question was variously interpreted by the teams, often resulting in redundancy which is evident from the large number of technical mistakes which are repeated throughout some technical proposals.

In addition, several of the standard questions were very general and the order in which they were asked may have been interpreted as redundant requests for information, which may have contributed to an overall lack of specificity in their responses. For example, in response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-09 stated: “[The challenge vehicle] will be using a laser range finding system, a video camera, a gyroscope, GPS, and a vibration sensor to determine the location of the path being taken, location of the vehicle, obstacles in the path, and the condition of the road/path surface.” ([38], p. 7). Team 2004-09 did not describe how the controlling intelligence uses this information except in the most general terms, although DARPA requested the teams “Describe the methodology for the interpretation of sensor data...” via a previous question, 2004 SQ 1.c.2 (see Table XXII), which also addressed vehicle state and navigation sensors.

DARPA exhibited concern with some team responses. For example:

- Team 2004-10

Team 2004-10 stated: “GC Review comments are in Attachment C.” ([77], p. 1), however the Team 2004-10 technical paper did not include Attachment C.

- Team 2004-20

Team 2004-20 stated: “The Government's questions from revisions 1 and 2, along with our replies, appear at the end of this document. In addition, per the Government's request, the replies have been incorporated into the text, in bold italic.” ([107], p. 1). Team 2004-20 maintained an extensive online repository which contained several revisions of their technical paper prior to the final version accepted by DARPA ([107]), including DARPA responses to their first and second revisions indicating that DARPA requested “technical specs (and/or manufacturer and model name if a commercial product)” for several sensors as well as other technical detail not reported by Team 2004-20 ([209]).

- Team 2004-21

Team 2004-21 responded to two sections labeled “DGC concerns” via their technical paper ([155]).

However, the author was unable to determine the extent of DARPA's involvement in a review of technical papers prior to the 2004 and 2005 GCE. There is no evidence this effort was comprehensive. The large number of technical mistakes in papers deemed “completely acceptable” by DARPA, and the failure of some teams to report “sufficient detail”, supports a conclusion the review, however extensive, was inadequate. Although DARPA established a penalty of disqualification for team challenge vehicles which “deviate substantially” from their description, no teams were disqualified for failure to report sufficient technical detail.

When the author concluded insufficient technical detail was reported to determine the total cost of team challenge vehicles, the author contacted DARPA to ask if DARPA had access to additional information not available from the technical papers. The author asked ([210]):

> I'm collecting pricing information for sensor technologies that were used in the 2004 and 2005 DARPA Grand Challenge, and I was wondering if DARPA collected this information, e.g., if the proposals from the teams, not the technical papers, included a cost breakdown that is public information or may be requested through a FOIA request.

DARPA responded:

> DARPA did not collect information from the teams that is publicly available.
>
> A good way to get the information you are looking for would be to start with the description in the technical papers and on the website, then to check with the manufacturers.

The author considers this validates the author's approach, and the results presented in this section refute the assertion that team technical papers reported sufficient technical detail to identify all sensors in use, let alone produce a reliable estimate of the total cost of challenge vehicles. In addition, the results presented in this section support a conclusion that DARPA was itself aware of the deficiencies in team technical papers but did not act to ensure the technical papers would be "the primary mechanism from which knowledge gained from this event is utilized in future research and development" ([207]).

V.E.1.d. Poor revision control

Several 2004 technical papers contained marks used to annotate revision such as colored or italicized text, highlighting, or comments, for example: Teams 2004-04, 2004-11, 2004-14, 2004-20, 2004-21, and 2004-25. DARPA required teams participating in the 2004 GCE to annotate revisions or include changes in a separate document. See paragraph V.E.1.a. Although DARPA did not establish a similar requirement prior to the 2005 GCE, the Team 2005-22 technical paper contained many annotated revisions.

As a result of these annotations, it is unclear if the technical paper represents the final published record of the teams prior to the 2004 QID or GCE or 2005 GCE or if the technical paper was incomplete, or a work in progress, when it was submitted to DARPA.

V.E.2. Additional sources of uncertainty

Several teams reported a cost for their challenge vehicles, either directly via team technical papers or the Journal of Field Robotics, or indirectly via another source. For example, teams participating in the 2005 GCE reported the following total costs and team sizes (source is [211] unless otherwise noted):

Table II. Reported cost and team size of selected team challenge vehicles.		
Team	Reported cost, dollars	Reported team size
2004-07	35,000[a]	N/A
2004-10	approximately $3 million[b]	N/A
2004-16	175,000[c]	N/A
2005-01	450,000[d]	N/A
2005-03	[e]	7
2005-06	650,000	12
2005-08	[f]	20
2005-12	125,000	14
2005-13	in excess of 3,000,000[g]	100+
2005-16	500,000	60
2005-18	120,000[h]	50
2005-20	500,000	18
2005-21	[f]	32
2005-22	60,000[i]	57+
2005-23	60,000[i]	

Notes:

[a] Team 2005-05 participated in the 2004 GCE as Team 2004-07. Team 2005-05 stated: "[The challenge vehicle] traveled 5.1 miles in the 2004 Challenge ... before stopping on a steep slope because of an excessively conservative safety limit on the throttle control. This was the fourth-greatest distance traveled in the 2004 DGC; a good performance considering [the challenge vehicle's] small total budget of $35,000." ([170], p. 528).

[b] Team 2004-10 reported a cost of "approximately $3 million" ([212]).

[c] Team 2004-16 stated: "Estimated Cost: $15,000 vehicle, $90,000 electronics, and $70,000 in-kind loaner equipment. Total hardware: $175,000. Not including thousands of hours of custom programming." ([139]).

[d] Team 2005-01 stated: "[Team 2005-01] will have spent roughly $450,000 on its 2005 DARPA Grand Challenge entry. This would have increased to $625,000, if the team had been charged for its MMW RADAR loaner unit." ([213]).

[e] Team 2005-03 did not report the cost of their challenge vehicle, but stated their

challenge vehicle cost “A lot!”.

[f] Teams 2005-08 and 2005-21 did not report the cost of their challenge vehicle.

[g] Team 2005-13 did not report the cost of their challenge vehicle, but stated their challenge vehicle was “Priceless”. However, Team 2004-10 reported a cost of “approximately $3 million” ([212]). Team 2004-10 participated in the 2005 GCE as Team 2005-13. The author concluded the cost of Team 2005-13's challenge vehicle exceeded the figure of “approximately $3 million” reported by Team 2004-10 due to continuing development. In addition, Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE. As a result, the combined cost of the Team 2005-13 and 2005-14 challenge vehicles was in excess of $3 million.

[h] Team 2005-18 stated: “$120K total equipment budget (excl. donations); CS/EE/ME 75abc + 24 SURFs.” ([197], p. 5).

[i] Teams 2005-22 and 2005-23 were co-participants during the 2005 GCE and stated the cost of their challenge vehicles was: “<$20,000 cash, with equipment donations worth ~$100,000”. The author evenly divided the $120,000 combined cost between the two teams.

However, without context, the costs reported by the teams are meaningless. It was immediately apparent that different accounting methods were used and that reported costs misrepresented the total cost of team challenge vehicles. In general, available objective evidence supports a conclusion that the published record did not report enough information with which to estimate the total cost of team challenge vehicles, although the author was able to identify additional sources of uncertainty during the review:

V.E.2.a. The cost of labor was not reported

From review of the published record, it is evident most teams did not report the cost of labor. Only one team which participated in the 2005 GCE, arguably, included the cost of student labor in reported cost: Team 2005-12.

Team 2005-12 stated the cost of their challenge vehicle was: “$125,000, including all travel expenses, hardware, and summer stipends for students”, and that their team was composed of: “1 professor and 1 grad student (supervisors) and 12 undergrads (who did all the work) over 18 months” ([211]). Team 2005-12 alternately stated: “[Team 2005-12] consists of a dedicated team of enrolled full-time undergraduate students, one graduate research assistant and several advising faculty.” ([185], p. 2), and identified more than 14 team members and “advisors”. In either case, the cost reported by Team 2005-12 ostensibly included the cost of undergraduate student labor during the summer as “summer stipends for students”.

In addition, Team 2005-12 stated: “The one Graduate Assistant contributed as part oh [*sic*] his graduate research requirement.” ([185], p. 2). As a result, the author concluded the “Graduate Assistant” was not compensated.

Team 2005-12 did not account for the cost of “advising faculty”.

The author considers it likely other teams accounted for the cost of labor, and that the cost of labor is included in the reported cost for some teams. However, there is no evidence this practice was widespread, or comprehensive. The author considers it more likely the cost of labor for student members of teams with limited Academic sponsorship or other teams on which students participated was not accounted for.

V.E.2.b. Labor cost estimation

Several teams reported general team composition, but not the cost of labor, and reported team composition indicated a large number of individuals worked on the team challenge vehicle. For example:

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “[The team] is a collaborative enterprise of students, volunteers, professionals and corporations...” ([11], p. 2 and [12], p. 2).

- Team 2005-15

Team 2005-15 stated: “Our team was formed in March 2003, in response to the announcement of the DARPA Grand Challenge 2004. Initially it comprised a team of scientists and engineers from Rockwell Scientific (RSC) of Thousand Oaks, CA, although many volunteers from other companies have joined the team.” ([53], p. 2) and via a footnote on the same page: “Our volunteers are employed at numerous companies including Amgen and Teradyne in the Thousand Oaks area and a number of our volunteers are Rockwell Scientific retirees.”.

- Team 2005-16

Team 2005-16 stated: “[Team 2005-16] brings together leading automotive engineers, artificial intelligence researchers, and experienced program managers...” ([195], pp. 1 - 2) and “The team consists of approximately 50 individuals that include... students, faculty, and alumni, and employees of [Team 2005-16] primary supporters and other nearby research labs. ([195], p. 3).

- Team 2005-17

Team 2005-17 stated: “[Team 2005-17] consists of faculty and students of the University of Louisiana at Lafayette and professionals from the Lafayette and Louisiana communities.” ([140], p. 2).

- Team 2005-18

Team 2005-18 stated: "[Team 2005-18] consists of over 50 undergraduates who have worked to conceive, design, build and optimize [the challenge vehicle]..." ([197], p. 1) and "As part of the plan to gain a competitive advantage, [Team 2005-18] invites industry experts to review the progress of the team at the end of each spiral of development and milestone (once per term). This review committee includes people from JPL, Northrop Grumman, STI and other companies. As part of the review, the industry experts submit requests for action (RFA's) on any component of the architecture that they feel needs work." ([197], p. 13).

As a result, the author considered using the reported number of team members to estimate the cost of labor, but concluded it would not be possible due to varying levels of experience or qualification. For example, as Team 2005-12 above, Teams 2005-22 and 2005-23 reported the composition of their teams: "40+ undergraduate students, 10 grad students, 2 faculty, 5+ volunteers" ([211]). There is a difference between the value of student labor, graduate student labor, and professional faculty labor. The same or similar differences exist between the value of engineer labor, project management labor, etc.

There is no evidence the cost of labor was differentiated based on experience or qualifications, but review of team descriptions available from the Archived Grand Challenge 2005 website ([19]) revealed individuals with varying levels of expertise and diverse backgrounds participated in the Grand Challenge.

In addition, the author concluded attempting to estimate the cost of labor by dividing the reported cost by the number of team members would not be possible, even after reducing the total cost by a fixed hardware cost. Dividing the reported cost by number of team members yielded annual salaries in the range of $2,000 to $54,000, which is a range so wide as to be meaningless.

The author likewise concluded attempting to estimate the cost of labor by multiplying an hourly rate by the number of hours reported would not be possible. Most teams did not report the number of team members, let alone the number of hours required to complete their challenge vehicles. Some teams reported thousands of hours of labor. For example, Team 2004-16 stated: "Estimated Cost: $15,000 vehicle, $90,000 electronics, and $70,000 in-kind loaner equipment. Total hardware: $175,000. Not including thousands of hours of custom programming." ([139]). Anecdotal evidence supports an assertion that most teams spent thousands of hours preparing for the 2004 and 2005 GCE.

To help establish perspective:

- The cost of labor for a team with 50 members working for one year (52 weeks with two weeks of unpaid vacation) 40 hours per week on average at an hourly rate of $10/hr would be $1 million.

- The cost of labor for a team with 50 members working for one year (52 weeks with two weeks of unpaid vacation) 60 hours per week on average, and being paid overtime, at an hourly rate of $10/hr would be $1.75 million.

- The cost of labor if the number of hours is limited to 2000 hours as the least possible number representative of "thousands of hours", at an hourly rate of $10/hr would be $200,000. This exceeds the reported cost of six of 13 challenge vehicles. See Table II.

V.E.2.c. Estimation of comparative costs

An alternate strategy considered by the author was estimation of comparative costs. Several teams reported comparative costs which could ostensibly be used to determine total cost. For example:

- Team 2005-01

Team 2005-01 stated: "There were Defense funded teams that could not be 'Completely Accepted' for the 2004 DARPA Grand Challenge, while we spent 5 cents to every dollar spent by other Defense teams." ([213]).

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: "By miles traveled at the Grand Challenge per dollars invested, the VT vehicles lead the field." ([214]).

However, it is unclear which teams Team 2005-01 identified as "Defense teams", or how Team 2005-01 arrived at an estimate of "5 cents to every dollar spent by other Defense teams"; and it is unclear how Teams 2005-22 and 2005-23 were able to determine "dollars invested" for all the teams which participated in the 2005 GCE.

As a result, the author concluded published comparative costs were unreliable, and that attempting to determine total cost by estimation of comparative costs would not be possible.

V.E.2.d. The cost of sensors was not reported

Although two estimates are publicly available which reported pricing information for some sensors in use by teams participating in the 2004 and 2005 GCE ([215] and [216]), the source of the pricing information reported by these documents is not available, and no team participating in the 2004 or 2005 GCE published a similar detailed cost breakdown, specifically listing the cost per sensor in use by the team. The author concluded these estimates are unreliable in the absence of corroborating evidence.

In addition, the author notes the price of sensors in use by the teams may depend on distributor, date procured, and reputation of the organization or institution procuring the sensor. Although the author has no direct evidence supporting variable pricing by manufacturers for sensors in use by teams participating during the 2004 and 2005 GCE, it is not an uncommon practice for manufacturers or distributors to variably price goods. As a result, teams with prior experience in autonomous vehicle development such as Teams 2005-13, 2005-14, and 2005-16 might have paid less for the same sensor in use by other teams based on reputation alone, or been able to negotiate more favorable prices based on prior experience.

V.E.2.d.i. Pricing information for most high-quality sensors is not available from published records

Pricing information for most sensors is not available from published records. The author does not consider manufacturer product literature, including pricing information, to which access is directly controlled by the manufacturer or indirectly controlled by an agent of the manufacturer to be published records. See Chapter XVI.

For example:

- SICK LIDAR sensors

SICK manufactured several models of Laser Measurement System (LMS) in use by teams which participated in the 2004 and 2005 GCE. However, pricing information for these sensors was not available from the manufacturer (e.g., [74] and [73]), and hyperlinks to distributors on the manufacturer website ([217]) led to a search dialogue for “local” distributors.

Realistically, there may be more of a difference in cost between SICK LMS 211-30106 and LMS 211-30206 LIDAR sensors than there is between LMS 211-30106 and LMS 220-30106 LIDAR sensors. Published estimates ([215] and [216]) reported pricing information for SICK LMS 211-30206 and SICK LMS 221-30206, but the reliability of either estimate could not be independently confirmed because SICK does not publicly disclose pricing information.

- Trimble DGPS receivers

Trimble manufactured several DGPS receivers in use by teams which participated in the 2004 and 2005 GCE. However, as with SICK, hyperlinks to distributors on the manufacturer website led to a search dialogue for “local” distributors ([192]).

The author noted the manufacturers most likely to publicly disclose pricing information were manufacturers of low-cost sensors such as state sensors, ultrasonic sensors, or cameras, e.g., SpaceAge Control, SensComp, and Unibrain. The author considers the greater competition in the market for such sensors may provide an incentive to the manufacturers of low-cost sensors to publicly disclose pricing information, and the greater cost of high-quality sensors may provide a disincentive to the manufacturers of such sensors to publicly disclose pricing information.

V.E.2.d.ii. Insufficient technical detail was reported to determine the total cost of reported sensors

The total cost of reported sensors includes the cost of accessories such as cabling and mounts, the individual cost of which is not significant but which collectively represent a cost that must be considered part of the total cost of the vehicle; the cost of optional accessories for alternate configurations which may not be included in the cost of the individual sensor, but which may have been in use by the teams, albeit not reported; and software. For example:

- Trimble DGPS receivers

The Trimble AgGPS 114 is a centerpiece surrounded by many other potential components, including the “AgGPS 70 RDL”, “AgGPS PSO Plus”, “AgGPS 170 Field Computer with Guidance”, “10 Hz positioning upgrade for AgGPS114”, “Everest Multi-path reduction for AgGPS 114”, and “OTHER AgGPS COMPONENTS/SYSTEMS” ([82]).

In addition, DGPS receivers typically receive free differential correction signals such as WAAS and USCG, but also differential correction signals from subscription services such as OmniSTAR or StarFire. Review of team technical papers revealed many teams used subscription services which provide differential correction signals. In general, the total cost of DGPS receivers should include the cost of subscription services such as OmniSTAR or StarFire.

- Image processing software

Team 2004-04 stated that a “Videre Design stereo vision system” was in use by the team. The author concluded this was a reference to an unknown Videre Design stereo camera pair. See paragraph V.C.4.b. However, like most STEREO sensors, Videre Design stereo camera pairs require the use of specific image processing algorithms to produce information useful to the controlling intelligence. It is for this reason that the author considers a stereo camera pair to be a high-quality sensor only if proven software for image processing was also in use by the team. See paragraph VI.B.1.a.i.

SRI's Small Vision System (SVS) has support for the stereo camera pairs manufactured by Videre Design ([97]). The cost of the “stereo vision system” in use by

Team 2004-04 therefore must include the cost of SRI's SVS, and, in general, the total cost of any sensor must also include the cost of software required to provide the controlling intelligence with useful information.

V.E.2.d.iii. Some teams referred to sensors to describe "systems" or reported the "system" as the sensor

Some teams reported the sensors comprising a "system" individually, or reported the "system" as the sensor. This was most prevalent for RADAR sensors. For example, Eaton and PRECO Preview RADARs have multiple emitters, which some teams reported as individual sensors. See paragraphs V.C.4.d., V.C.20.b., V.C.21.b., V.C.23.c., V.C.26.b., V.C.27.b., and V.C.40.e. for specific examples. Several VISION or STEREO sensors with multiple cameras were also described as "systems". See paragraphs V.C.34.c., V.C.39.b., and V.C.45.c. for specific examples.

When the author determined the intent of the team was unambiguous and required no additional evaluation, he did not document occurrences of this discrepancy via paragraph V.C. For example:

- Team 2004-15

Team 2004-15 stated: "An active 24.725 GHz Doppler radar system (Eaton VORAD EVT-300) with a sensing horizon of 100 meters and 12 degree field of view will also be utilized for obstacle detection/avoidance as well as enhanced road following capability. The radar *system* will include a forward-looking antenna as well as range-gated side sensors." ([137], p. 3, *emphasis added*). Because Team 2004-15 clearly described the Eaton EVT-300 as a system which included one "forward-looking antenna" and two "side sensors", the author concluded one Eaton EVT-300 *system* was in use by the team.

- Team 2005-08

Team 2005-08 stated: "The SCC radars have a 15 degree field of view. For [the challenge vehicle], three SCC radars are configured across the front of the vehicle in a manner to provide a 45 degree field of view." ([173], p. 9). The author concluded three Delphi Forewarn ACC3 RADAR *sensors* were in use by Team 2005-08 based on the collective field-of-view reported by Team 2005-08.

V.E.2.e. The cost of equipment donated or loaned to the teams was not reported

Several teams directly or indirectly reported the cost of equipment donated or loaned to the teams. For example:

- Team 2004-16

Team 2004-16 stated: “Estimated Cost: $15,000 vehicle, $90,000 electronics, and $70,000 in-kind loaner equipment. Total hardware: $175,000.” ([139]).

- Team 2005-01

Team 2005-01 stated: “[Team 2005-01] will have spent roughly $450,000 on its 2005 DARPA Grand Challenge entry. This would have increased to $625,000, if the team had been charged for its MMW RADAR loaner unit.” ([213]).

- Team 2005-10

Team 2005-10 stated: “In the end, most of the cost of the project was covered by corporate donations of equipment.” ([176], p. 8).

- Team 2005-18

Team 2005-18 reported a “$120K total equipment budget (excl. donations)” ([197], p. 5).

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 reported “equipment donations worth ~$100,000” ([211]).

However, most teams which participated in the 2004 and 2005 GCE did not report the cost of equipment donated or loaned to the teams.

V.E.2.e.i. <u>The cost of computing resources was not reported</u>

In general, the cost of sensors does not include the cost of computer or networking hardware required to integrate sensor data, unless a COTS product was in use by the team for this purpose, yet the total cost includes the cost of computing resources which provide useful information to the controlling intelligence.

V.E.2.f. <u>Confidential and proprietary appendixes conceal technical detail</u>

Via paragraph 4.3.3 of revision “April 1.2” of the 2004 GCE rules ([1]) DARPA stated: “DARPA will treat the technical papers as team proprietary information in their entirety until the conclusion of the 2004 Challenge, at which time the papers will be available to the public. Technical papers containing an attachment of information that is designated by the Team as proprietary information will not be made available with the proprietary attachment.”

Several teams which participated in the 2004 GCE included confidential or proprietary appendixes in their technical papers. The confidential or proprietary appendixes conceal technical detail. For example:

- Team 2004-03

Team 2004-03 referred to three "confidential" appendixes: "1A1-0", "1A1-1", and "1A2" ([92], p. 3) which provided information about challenge vehicle "mobility", and one non-confidential appendix "3D2", which provided information about the placement of E-stop switches on the challenge vehicle. Team 2004-03 was the only team to select a motorcycle as the platform for their challenge vehicle for either the 2004 or 2005 GCE (see Tables XIV, XV, and XVI).

DARPA published neither the Team 2004-03 confidential appendixes nor the non-confidential appendix. However, DARPA later noted: "The independent technical evaluation team identified the following technology from Grand Challenge 2004 noteworthy": "Dynamically balancing motorcycles" ([3], p. 10). As a result, the author considers this supports a conclusion that there was perceived value in the Team 2004-03 intellectual property.

- Team 2004-06

Team 2004-06 stated: "The entire contents of this paper are considered proprietary and confidential to DARPA." ([114], p. 7). This statement appears on the first page of the Team 2004-06 "Addendum to Technical Paper", however DARPA published the paper in its entirety, including the addendum.

- Team 2004-10

Team 2004-10 stated: "Four Attachments describe the vehicle design. The original GC questions are in Attachment B. GC Review comments are in Attachment C." ([77], p. 1). Team 2004-10 did not report the information Attachments A or D provided, and the technical paper did not include any of the attachments to which Team 2004-10 referred.

- Team 2004-22

Team 2004-22 twice referred to a "proprietary annex": "Video Processing—See Proprietary Annex" ([157], p. 3), and "Actual speeds in tight turns is addressed in the proprietary annex." ([157], p. 7); and once to an "attached annex": "Novatel ProPac-LB-HB satellite-based Differential GPS... Specifications are in attached annex" ([157], p. 2). Team 2004-22 also referred to a "presentation": "Attached PowerPoint presentation depicts the area of coverage for the new imagery." ([157], p. 4). DARPA did not publish either the Team 2004-22 proprietary annex, attached annex, or presentation.

- Team 2004-23

Team 2004-23 stated: “The vision system consists of 6 CCD digital color cameras. Two pairs are used to provide stereovision information (both forward and rear looking). The two single cameras will sense the terrain in front and behind the truck and provide free-space estimation and path/road estimation.” and “The vision system is a work in progress with the system being developed and tested initially in Italy by Prof. Alberto Broggi’s group.” ([159], p. 8).

Although Team 2004-23 did not refer to a confidential or proprietary appendix or annex, the team technical paper ([159]) essentially describes a vision processing system and, as DARPA later noted: “The independent technical evaluation team identified the following technology from Grand Challenge 2004 noteworthy”: “Custom hardware solution for low-cost, real-time stereo algorithm with reflexive planning” ([3], p. 10). Teams 2004-06, 2004-22, and 2004-23 each developed a custom vision processing system for use as a path and obstacle detection sensor. The author considers this supports a conclusion that there was perceived value in Team 2004-23 intellectual property, as well as the intellectual property of Teams 2004-06 and 2004-22.

In addition, some teams specifically referred to the value of intellectual property in their team technical papers or other published records. For example, Team 2005-15 stated: “A limited liability company ... was created as the legal entity for ownership of the vehicle and accessories and for participation in the event. [The LLC] ... will own the team intellectual property and is positioned to transition into a company that will exploit its autonomous vehicle technology after the Grand Challenge series is complete.” ([53], p. 2), and Team 2005-17 twice stated: “The algorithm is being evaluated by the University for its IP value. Hence, its details are not being disclosed in this public document.” ([140], p. 9).

As a result, the author concluded some teams were not motivated to disclose relevant technical information due to the perceived value of intellectual property that would be generated as a result of the 2004 and 2005 GCE.

Six teams which participated in the 2005 GCE referred to proprietary technologies via their technical papers. However, no teams which participated in the 2005 GCE included confidential or proprietary appendixes in their technical papers. DARPA did not refer to confidential or proprietary appendixes prior to the 2005 GCE, but stated ([2], p. 18):

> Other than the required technical paper and information already in the public domain, DARPA will not publicly release information regarding a team’s

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technical approach without permission from the team
leader.

DARPA claims no intellectual property (IP) rights from
entrants, semifinalists, finalists, or the winner...
All trade secrets, copyrights, patent rights, and
software rights will remain with each respective team.
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V.E.2.g. Anecdotal evidence

The author observed a difference in the amount of technical information disclosed by technical proposals submitted by teams with significant corporate sponsorship and other technical proposals during the comprehensive review of technical papers. Some teams with significant corporate sponsorship (e.g., Teams 2004-10, 2004-13, 2004-14, and 2004-18) seemed to disclose more relevant technical information than other teams.

A comment by the Team 2004-05 team leader may provide some insight into this observation. The Team 2004-05 team leader asserted that teams such as Team 2004-10 "largely pulled together a range of existing, expensive components that companies were keen to give away in order to attract the government's attention." ([218]). As a result, the author proposes the decision to disclose relevant technical information may have been influenced by corporate sponsorship, in particular, a "quid pro quo" relationship in which equipment was donated or loaned to some teams in exchange for publicity or other exposure resulting from team use of the equipment. The many press releases detailing the use of a manufacturer's technology, equipment, or components by teams participating in the 2004 QID or GCE or 2005 GCE, some of which are referenced herein, support this assertion.

However, the author also concluded the use of COTS components and high-quality sensors were key factors contributing to success. As a result, although the author considers publicity or other exposure a reasonable explanation for the difference in the amount of technical information disclosed by teams with significant corporate sponsorship, the author also considers the incidental publicity or other exposure resulting from corporate sponsorship an unfortunate but unavoidable consequence of an event such as the Grand Challenge, which encouraged existing defense contractors to provide corporate sponsorship, but not participate directly.

Team sponsorship was not considered when evaluating the amount of technical information disclosed by teams.

Evidence such as teams referring specifically to the formation of business structures such as a Limited Liability Company and the existence of confidential or proprietary appendixes revealed the focus of many teams was on monetizing their intellectual property, not on sharing technical detail. See paragraph V.E.2.f. Anecdotal evidence such as the distribution of “shares” revealed the focus of many teams was on prize distribution.

Although Team 2005-10 stated: “We are especially grateful to those fellow Grand Challenge competitors who have been willing to share their knowledge directly and on the DARPA GC discussion forum. [The Team 2004-05 team leader] in particular has distinguished himself for his spirit of cooperation and willingness to share information.” ([176], p. 7), the Team 2004-05 team leader's attitude was not prevalent. More teams referred to the non-disclosure of information than the sharing of information.

In addition, the author noted a difference in the approach of teams with moderate or extensive academic sponsorship as “compete to teach” and “compete to win”. Some teams with a primary group identity as “Academic”, such as Teams 2004-25, 2005-04 and 2005-12, referred specifically to participation in the Grand Challenge as a teaching opportunity, e.g., as part of an existing course or independent research. For example:

- Team 2004-25

Team 2004-25 stated: “[Team 2004-25] is using this Challenge as a senior design experience for undergraduate Mechanical Engineering students.” ([49], p. 13).

- Team 2005-04

Team 2005-04 stated: “A two Quarter 'Capstone Design Course' sequence was initiated and helped investigate new ideas, apart from inspiring students.” ([169], p. 7).

- Team 2005-12

Team 2005-12 stated: “Underclassmen have participated as either summer interns and/or on an extra-curricular basis, while upperclassmen have received independent research or senior thesis credit for their research contribution to the project. The one Graduate Assistant contributed as part oh [*sic*] his graduate research requirement.” ([185], p. 2).

- Team 2005-18

Team 2005-18 stated: “Through a new course in multi-disciplinary project design, we have had over 50 students participate in conceiving, designing, implementing and testing our new vehicle...” ([197], p. 2).

Other teams with a primary group identity as “Academic”, such as Teams 2005-13, 2005-14, and 2005-16, all of which successfully completed the 2005 GCE did not appear to have the same focus on the Grand Challenge as a teaching opportunity. For this reason, the author chose to focus on participation, in lieu of competition. See Chapter XVI.