CHAPTER VI. HIGH-QUALITY OBSTACLE AND PATH DETECTION SENSORS

VI.A. Discussion

During the review of 2004 and 2005 technical proposals, the author noted an increase in the number of major (i.e., not discounted) obstacle and path detection sensors in use by teams which participated in the 2004 and 2005 GCE, and a corresponding decrease in discounted obstacle and path detection sensors and state sensors.

VI.B. Analysis

The author reviewed the published record in an attempt to quantify the number of major obstacle and path detection sensors in use by the teams, in particular sensors which were considered high-quality. Environment sensors were first classified by type: "VISION", "STEREO", "RADAR", or "LIDAR". Environment sensors were then classified by quality. Discounted sensors were eliminated from consideration as described in paragraph V.B.4. Sensors of each type were classified as high-quality sensors in accordance with paragraphs VI.B.1., VI.B.2., and VI.B.3. In general, high-quality sensors were considered to be those sensors which provided discrete information about the environment, such as a point-map (using depth-to-LIDAR return) or point-cloud (using depth-to-pixel) or obstacle location relative to the challenge vehicle, at a speed at which the challenge vehicle's controlling intelligence was able to reliably interpret.

VI.B.1. VISION sensors

The author divided vision sensors in use by the teams into two categories: "Stereo Camera Pair" and "Other Cameras".

VI.B.1.a. Stereo camera pair

The author considered a combination of two or more cameras to be a stereo camera pair if clearly described as a stereo camera pair by the team or manufacturer. The author considers a stereo camera pair to be a high-quality sensor if proven software for image processing was also in use by the team.

VI.B.1.a.i. High-quality stereo camera pairs

High-quality stereo camera pairs included the following known STEREO sensors:

- Point Grey Bumblebee.
- Videre Design Stereo Vision System (SVS).
- Team 2004-17 stereo camera pairs. Four Point Grey Dragonfly cameras were in use by Team 2004-17 as two stereo camera pairs during the 2004 QID and GCE.

See paragraph V.C.17.c. Team 2004-17 stated: "One short range and one long range pair of black and white stereovision cameras will produce point clouds at 30 Hz that we will process into local terrain maps at the same rate. This computation will be done with the Small Vision System purchased from Videre Systems." ([142], p. 5).

- Team 2005-08 Sony DFW-VL500 stereo camera pair. Two Sony DFW-VL500 cameras were in use by Team 2005-08 during the 2005 GCE as a stereo camera pair. See paragraph V.C.33.d. Team 2005-08 stated: "The low level stereo processing is performed using the Small Vision System (SVS) software from Videre Design." ([173], p. 11).

- Team 2005-15 stereo camera pair. One stereo camera pair was in use by Team 2005-15 during the 2005 GCE. See paragraph V.C.39.b. Team 2005-15 stated: "ARC Seibersdorf ... provided their stereovision system for feature detection." ([53], p. 3) and "...a stereo vision system jointly developed by Seibersdorf research and ACV, is used." ([53], p. 9). Although Team 2005-15 described this sensor as "novel", the author concluded it was likely proven software for image processing was also in use by the team.

- Team 2005-18 stereo camera pairs. Four Point Grey Dragonfly cameras were in use by Team 2005-18 during the 2005 GCE as two stereo camera pairs. See paragraph V.C.42.b. 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).

High-quality stereo camera pairs included the following unknown STEREO sensors, as described by team technical proposals:

- Team 2004-18 unknown stereo camera pair. One unknown stereo camera pair was in use by Team 2004-18 during the 2004 QID and GCE. See paragraph V.C.18.g. Team 2004-18 stated: "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.", "...the SVS includes SRI's patent pending Stereo Engine algorithm...", and "...a cloud of 3D surface points in front of the vehicle is produced and becomes accessible by [Team 2004-18's] custom software." ([48], p. 5).

- Team 2004-23 unknown stereo camera pairs. Four unknown CCD digital color cameras were in use by Team 2004-23 as two stereo camera pairs. See paragraph V.C.23.e. Via the team technical proposal ([159]), Team 2004-23 described the image processing software and also how the image processing software was proven.

- Team 2005-04 unknown stereo camera pair. One unknown stereo camera pair was in use by Team 2005-04 during the 2005 GCE. See paragraph V.C.29.c. Team 2005-04 stated: “[The challenge vehicle] was developed in partnership with the University of Karlsruhe, which developed the vision system.” ([169], p. 2) and “The Vision system was developed entirely separately by the University of Karlsruhe team in Germany, and then integrated with the Sensor Fusion set-up... The cross-Atlantic cooperative development was similar in nature to the one we initiated with an Italian team in 2004, while developing [the Team 2004-23 challenge vehicle].” ([169], p. 7). Based on the description of the Team 2004-23 challenge vehicle unknown stereo camera pairs, the author considers it likely a similar effort was made by Team 2005-04 to prove the image processing software.

- Team 2005-21 unknown trinocular camera system. An unknown trinocular camera system was in use by Team 2005-21 during the 2005 GCE. See paragraph V.C.45.c. Via the team technical paper ([160]), Team 2005-21 described the image processing software and also how the image processing software was proven.

VI.B.1.a.ii. Other stereo camera pairs

Stereo camera pairs which were not considered to be high-quality sensors included:

- Team 2004-03 unknown Cognex cameras. Two unknown Cognex cameras were in use by Team 2004-03 during the 2004 QID and GCE. See paragraph V.C.3.b. Team 2004-03 reported “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.” were in use by the team ([94]). Because these cameras were used to create a “3D scene of the obstacles in front of the vehicle”, the author concluded these cameras were in use as a stereo camera pair. Team 2004-03 reported no additional identifying information for the software in use by the team.

- Team 2004-06 Digital Auto Drive. A proprietary stereo camera pair was in use by Team 2004-06 during the 2004 QID and GCE. See paragraph V.C.6.a. Team 2004-06 participated in the 2005 GCE as Team 2005-03. A proprietary LIDAR sensor was in use by Team 2005-03. See paragraph V.C.28.a. Team 2005-03 stated: “Lessons learned from GC I drove the requirements for the LADAR terrain mapping and obstacle detection system...” ([33], p. 6). Although Team 2004-06 stated: “We are unaware of any other high quality vision systems in existence...” ([114], p. 7), the author concluded the proprietary stereo camera pair in use by Team 2004-06 was not a high-quality stereo camera pair because Team 2004-06 reported no additional identifying information for the software in use by the team and the proprietary stereo camera pair was not in use by Team 2005-03 during the 2005 GCE.

- Team 2004-19 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2004-19 during the 2004 QID. See paragraph V.C.19.a. 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). Team 2004-19 reported no additional identifying information for the software in use by the team.

- Team 2004-24 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2004-24 during the 2004 QID and GCE. See paragraph V.C.24.c. Team 2004-24 reported no additional identifying information for the software in use by the team.

- Team 2005-07 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2005-07 during the 2005 GCE. See paragraph V.C.32. Team 2005-07 reported no additional identifying information for the software in use by the team.

- Team 2005-10 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2005-10 during the 2005 GCE. See paragraph V.C.35.c. Team 2005-10 stated: "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). Based on the results of other teams which independently implemented image processing algorithms during the 2004 and 2005 GCE, the author considers it likely the software implementing the algorithm described by Team 2005-10 was unproven.

- Team 2005-20 unknown stereo camera pair(s). Unknown stereo camera pair(s) were in use by Team 2005-20 during the 2005 GCE. See paragraph V.C.44.c. Team 2005-20 reported no additional identifying information for the software in use by the team.

VI.B.1.b. <u>Other cameras</u>

All other cameras are considered to be VISION sensors. The author does not consider VISION sensors to be high-quality sensors.

VI.B.2. RADAR sensors

The author divided RADAR sensors in use by the teams into two categories: "Navigation RADAR" and "Other RADAR".

VI.B.2.a. <u>Navigation RADAR</u>

The author considered any RADAR sensor which provided the range, relative velocity, and azimuth to target for multiple targets to be navigation RADAR. The author considers navigation RADAR a high-quality sensor. Navigation RADAR included the following known RADAR sensors:

- Epsilon Lambda ELSC71-1A. The Team 2004-21 technical proposal incorporated a specification sheet for the Epsilon Lambda ELSC71-1A as an appendix. The appendix stated: "Obstacle data reported includes range; [*sic*] azimuth angle, elevation angle, relative velocity, and signal return amplitude." ([155], p. 14).

- Eaton EVT-300 when interfaced with the Eaton VBOX. Although Eaton stated the Eaton EVT-300 provides: "Accurate range, velocity and azimuth on up to 20 vehicles or objects within a range of 350 feet." ([162]), the Eaton EVT-300 "Driver Display Unit" does not provide the range, relative velocity, and azimuth to target. However, Eaton reported the Eaton VBOX provides "Target range, speed, [and] angle relative to host radar" ([106]) as output via an RS-232 port.

- Navtech DS2000. Navtech stated: "With the scanner and raydome [*sic*] the unit provides a full 360 degrees scan at 2.5 Hz with target ranges up to 200m and range accuracy down to +/- 0.03m." and "As standard the system will provide range and bearing information to the nearest target that is above a predefined size." ([219]).

Examples of navigation RADAR included the following unknown RADAR sensors, as described by team technical proposals:

- Team 2004-05 unknown Eaton RADAR. One unknown Eaton RADAR was in use by Team 2004-05 during the 2004 QID. See paragraph V.C.5.g. The author considers is likely the Team 2004-05 unknown Eaton RADAR would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the "Eaton Vorad VBOX 83001-001" in use by the team.

- Teams 2004-13 and 2004-14 unknown Epsilon Lambda RADAR. One unknown Epsilon Lambda RADAR sensor was in use by Teams 2004-13 and 2004-14 during the 2004 QID and GCE. See paragraph V.C.13.f. and V.C.14.f. The author considers it likely the unknown Epsilon Lambda RADAR would have had capabilities characteristic of the Epsilon Lambda ELSC71-1A.

- Team 2004-16 unknown RADARs. Unknown RADARs were in use by Team 2004-16 during the 2004 QID and GCE. See paragraph V.C.16.d. Team 2004-16 stated: "Radar/sonar subsystem identifies large or small objects and radar can estimate velocity for distinguishing moving vehicles from stationary objects..." and "Differential signals from sonar and radar help to estimate location of object [*sic*]." ([138], pp. 3 - 4). The author concluded the Team 2004-16 unknown RADARs had capabilities characteristic of navigation RADAR.

- Team 2004-23 unknown Eaton RADARs. Two unknown Eaton RADARs were in use by Team 2004-23 during the 2004 QID and GCE. See paragraph V.C.23.c. Team 2004-23 stated: “2 Eaton-Vorad radars are mounted (front and rear) for providing 150 m range target tracking.” ([159], p. 9). The author considers it likely the Team 2004-23 unknown Eaton RADARs would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2004-24 unknown Eaton RADAR. One unknown Eaton RADAR was in use by Team 2004-24 during the 2004 QID and GCE. See paragraph V.C.24.e. 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). The author considers is likely the Team 2004-24 unknown Eaton RADAR would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2004-25 unknown Eaton RADARs. Two unknown Eaton RADARs were in use by Team 2004-25 during the 2004 QID and GCE. See paragraph V.C.25.f. Team 2004-25 stated: “The radar system actively distinguishes obstacles moving relative to the vehicle from the surroundings. The radar system and laser rangefinders are used to determine the direction, size, and speed of obstacles.” ([49], p. 10). The author considers is likely the Team 2004-25 unknown Eaton RADARs would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2005-20 unknown RADAR(s). Unknown RADAR(s) were in use by Team 2005-20 during the 2005 GCE. See paragraph V.C.44.b. Team 2005-20 stated: “The RADAR system, for example, preprocesses the data to locate obstacles in the vehicle path. It receives broadcast messages from the vehicle location navigation computer to determine a global position of the obstacle. Based on a confidence of the obstacle, the RADAR computer broadcasts the obstacle parameters including position in both local and global coordinates along with obstacle size to the path planner map.” ([56], p. 7). Based on the Team 2005-20 description of the “RADAR system”, the author considers it likely the Team 2005-20 unknown RADAR(s) provided the range, relative velocity, and azimuth to target for multiple targets.

VI.B.2.b. Other RADAR

All other RADAR sensors are considered to be “Other RADAR”. The author does not consider other RADAR sensors to be high-quality sensors. Other RADAR sensors include:

- All vehicle anti-collision or obstacle avoidance RADAR, including the Eaton EVT-300 when not interfaced with the Eaton VBOX, Amphitech OASys, Preco Preview, and Delphi Forewarn ACC3.

- All “short-range” RADAR sensors.

- All Doppler RADAR sensors.

- Team 2004-04 unknown long-range RADAR. One unknown long-range RADAR was in use by Team 2004-04 during the 2004 QID and GCE. See paragraph V.C.4.d. Team 2004-04 participated in the 2005 GCE as Team 2005-02. Team 2005-02 alternately stated an unknown Eaton RADAR sensor was in use by the team via the team technical proposal ([167]), and not in use by the team via the Journal of Field Robotics ([50]). See paragraph V.C.27.b. Team 2004-04 stated: “Because of the wide field of view of the RADAR system and the limited range resolution, the RADAR system will be used as a 'free space' detector.” ([44], p. 6). Team 2004-04 did not report sufficient technical detail to conclude the unknown long-range RADAR provided the range, relative velocity, and azimuth to target for multiple targets, and was not in use as a vehicle anti-collision RADAR.

- Team 2004-15 Eaton EVT-300. One Eaton EVT-300 was in use by 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). The author concluded this sensor was in use as a vehicle anti-collision RADAR.

- Team 2005-01 unknown Eaton RADAR. One unknown Eaton RADAR was in use by Team 2005-01. See paragraph V.C.26.b. Team 2005-01 did not report sufficient technical detail to conclude the unknown Eaton RADAR would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2005-04 Eaton EVT-300. One Eaton EVT-300 was in use by Team 2005-04 during the 2005 GCE. Team 2005-04 stated: “One radar (the Eaton-Vorad 300 EVT) is pointed straight ahead and is mainly for long distance obstacle detection at high speed.” ([169], p. 8). The author concluded this sensor was in use as a vehicle anti-collision RADAR, not navigation RADAR.

- Team 2005-04 unknown RADAR. One unknown RADAR was in use by Team 2005-04 during the 2005 GCE. See paragraph V.C.29.b. Team 2005-04 did not report sufficient technical detail to conclude the unknown RADAR provided the range, relative velocity, and azimuth to target for multiple targets.

VI.B.3. LIDAR sensors

The author divided LIDAR sensors in use by the teams into two categories: scanning laser range finders and other LIDAR sensors.

VI.B.3.a. Scanning laser range finders

The author considers scanning laser range finders to be high-quality sensors. Examples of scanning laser range finders included the following known LIDAR sensors:

- All SICK LMS LIDAR sensors. SICK LMS LIDAR sensors were the most popular sensors in use by teams which participated in either the 2004 or 2005 GCE. Based on their popularity, the author considers all unknown SICK LIDAR sensors to be SICK LMS LIDAR sensors, unless otherwise noted.

- All Riegl LIDAR sensors.

- The Optech ILRIS-3D.

Examples of scanning laser range finders included the following unknown LIDAR sensors, as described by team technical proposals:

- Team 2004-11 unknown scanning laser range finder. One unknown scanning laser range finder was in use by Team 2004-11. See paragraph V.C.11.b.

- Team 2004-24 unknown LIDAR sensor. One unknown LIDAR sensor was in use by Team 2004-24 during the 2004 QID and GCE. See paragraph V.C.24.d. 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). Based on the use of the unknown LIDAR sensor for “solid model construction”, the author concluded this sensor was a scanning laser range finder capable of providing a point-map.

- Team 2005-03 Digital Auto Drive. A proprietary LIDAR sensor was in use by Team 2005-03 during the 2005 GCE. See paragraph V.C.28.a. The proprietary LIDAR sensor described by Team 2005-03 is a scanning LIDAR sensor with a 360-degree field-of-view similar to scanning LIDAR sensors with a more limited field-of-view in use by teams which participated in the 2005 GCE.

- Team 2005-20 unknown LIDAR sensor(s). Unknown LIDAR sensor(s) were in use by Team 2005-20 during the 2005 GCE. See paragraph V.C.44.a. No other team which participated in the 2005 GCE used non-scanning, or simple, laser range finders. As a result, the author considers it likely the unknown LIDAR sensor(s) in use by Team 2005-20 were scanning laser range finders.

- Team 2005-21 unknown Ibeo LIDAR sensors. One unknown Ibeo LIDAR sensor was in use by Team 2005-21 during the 2005 GCE. See paragraph V.C.45.b. An Ibeo “Case Study” described the Ibeo LIDAR sensor in use by Team 2005-21 as a “laser scanner” ([204]).

VI.B.3.b. Other LIDAR

All other LIDAR sensors are considered to be "Other LIDAR". The author does not consider other LIDAR sensors to be high-quality sensors. Examples of other LIDAR sensors include:

- Laseroptronix LDM 800-RS232. Laseroptronix stated the Laseroptronix LDM 800-RS232 is a "pulsed laser distance meter / laser range finder" ([220]), not a scanning laser range finder.

- Laseroptronix Sea-Lynx. Laseroptronix stated that, although the "passive" and "active" modes of the Laseroptronix Sea-Lynx function as an image-intensified camera the difference between which is the use of the built-in "laser illumination lamp" to provide a source of light for image intensification, the camera also has a "combined" mode in which "the camera is scanned all over the distance depth in gated mode and all is viewed in one image" ([221]). As a result, the author considers the Laseroptronix Sea-Lynx to be a combined VISION/LIDAR sensor, which uses LIDAR to function as a ranged VISION sensor. Because the Laseroptronix Sea-Lynx outputs what is essentially a television signal (PAL), and does not function primarily as a scanning laser range finder, the author does not consider it to be a high-quality LIDAR sensor.

- Team 2004-11 unknown long-range laser ranger. One unknown long-range laser ranger was in use by Team 2004-11. See paragraph V.C.11.b. Team 2004-11 did not report sufficient technical detail to determine if the long-range laser ranger described by the team was a scanning laser range finder.

- SICK DME 2000. SICK stated the SICK DME 2000 is a "distance measuring device", not a scanning laser range finder ([222]).

VI.C. Results

Results are presented in Tables XXXVI, XXXVII, XXXVIII, and XXXIX, and summarized in Tables XL, XLI, XLII, and XLIII.

VI.C.1. Differences in the number of teams using high-quality sensors from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 or 2005 GCE:

- There was an increase in the number of teams using high-quality STEREO sensors from 33 percent to 39 percent, a difference of 6 percent.

- There was an increase in the number of teams using high-quality LIDAR sensors from 87 percent to 96 percent, a difference of 9 percent.

- There was a decrease in the number of teams using high-quality RADAR sensors from 60 percent to 13 percent, a difference of 47 percent.

VI.C.2. Differences in the number of high-quality sensors in use

As an average of the number of high-quality sensors of each type in use divided by the total number of teams using sensors of that type during the 2004 and 2005 GCE:

- There was no net change in the number of STEREO sensors in use.

- There was an increase in the number of LIDAR sensors in use per team from 2.3 sensors per team to 3.6 sensors per team.

- There was a decrease in the number of RADAR sensors in use per team from 1.2 sensors per team to 1.0 sensors per team.

VI.D. Conclusions

Teams which participated in the 2004 GCE completed 1.95 miles of the 2004 GCE course, on average, or approximately 1.4 percent of the reported course length of 142 miles. Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average, or approximately 36.7 percent of the reported course length of 131.6 miles.

Based on the analysis, two teams which participated in the 2005 GCE stand out: Teams 2005-06 and 2005-12. Team 2005-06 implemented obstacle and path detection using two vertically-aligned LIDAR sensors on an oscillating mount, and, although Team 2005-12 completed only 9.5 miles of the 2005 GCE course, their later performance supports a conclusion they implemented an obstacle and path detection strategy using one Point Grey Bumblebee stereo camera pair. Both teams equaled or exceeded the performance of teams using a greater number and variety of sensors.

Based on the increase as a percentage of the total course length completed from 2004 to 2005, the author concluded there was a correlation between the following key factors and the average number of miles of the 2004 and 2005 GCE courses the teams completed. The author is not attempting to imply causation. However, the following key factors were common to teams which participated in both the 2004 and 2005 GCE, in general.

VI.D.1. Reduce the number of obstacle and path detection sensors in use by eliminating other sensors

Not only was there a decrease in the number of teams using other cameras, other LIDAR, and other RADAR from 2004 to 2005, but there was a decrease in the number of sensors, i.e., other cameras, other LIDAR, and other RADAR sensors, in use by teams which participated in the 2004 and 2005 GCE.

Overall, the author concluded reduction in complexity was a key factor, and considers the reduction in the number of obstacle and path detection sensors in use by eliminating other sensors an example of reducing complexity. See paragraph XIV.B.

VI.D.2. Use high-quality sensors which provide a point-map of the environment

High-quality STEREO and LIDAR sensors provide a point-map of the environment. Overall, there was an increase in the number of teams using high-quality STEREO and LIDAR sensors, and an increase in the number of sensors of each type in use by each team. The evidence supports a conclusion high-quality LIDAR sensors were easier to integrate, which may explain why high-quality LIDAR sensors were in use by approximately 87 or 96 percent of teams which participated in the 2004 or 2005 GCE, respectively. The number of high-quality LIDAR sensors in use by teams increased from 2.3 to 3.6 sensors, an average increase of approximately one LIDAR sensor per team.

Several teams cited this capability in their technical proposals. For example, an unknown Videre Design stereo vision system was in use by Team 2004-04. See Table XXV. Team 2004-04 stated: "The stereo vision system will be the three dimensional sensor used on [the challenge vehicle]. Its primary purpose will be to provide a dense, albeit noisy, cloud of three dimensional sensor data to our fusion algorithms at a high rate. While the data may in fact be noisy, it will provide valuable information about the presence of objects of interest at distances and elevations outside the field of view of the LADAR system." ([44], p. 8).

By comparison, high-quality RADAR does not provide a point-map of the environment. Several teams which reported navigation RADAR was in use stated the information it provided was of limited utility or the sensor was difficult to integrate, or later reported navigation RADAR was not in use during the 2004 or 2005 GCE. For example:

- Team 2004-07

One Epsilon Lambda ELSC71-1A was in use by Team 2004-07 during the 2004 GCE. See Table XXV. Team 2004-07 stated: "The radar has been shown to give a minimal level of functionality but it is not clear if it will deliver the expected level of performance." ([46], p. 9).

- Team 2004-10

Team 2004-10 reported a Navtech DS2000 was in use by the team, but later stated: "The RADAR was not integrated with the primary navigation system due to difficulties extracting noise free data." ([39], p. 14). The author concluded the Navtech DS2000 was not in use by Team 2004-10 during the 2004 GCE. See paragraph V.C.10.c. The author concluded the Navtech DS2000 was not in use by Team 2004-10 because it was difficult to integrate.

- Team 2004-16

Unknown RADARs were in use by Team 2004-16. See Table XXV. Team 2004-16 participated in the 2005 GCE as Team 2005-17. Team 2005-17 stated: "The radar and sonar sensors are removed." ([140], p. 2). See paragraph V.C.16.d. The author considers it likely the unknown RADARs were removed because the information they provided was of limited utility or the RADARs were difficult to integrate.

- Team 2004-25

Two unknown Eaton RADARs were in use by Team 2004-25. See Table XXV. Team 2004-25 participated in the 2005 GCE as Team 2005-22. Neither Team 2005-22 nor its co-participant Team 2005-23 referred to RADAR sensors in use by the team. See paragraph V.C.25.f. The author considers it likely the unknown Eaton RADARs were not in use by either Team 2005-22 or 2005-23 because the information they provided was of limited utility or the RADARs were difficult to integrate.

- Team 2005-02

Team 2005-02 reported an unknown Eaton RADAR was in use by the team, but did not report the unknown Eaton RADAR was in use during the 2005 GCE, and later 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. See paragraph V.C.27.b. The author considers it likely the unknown Eaton RADAR was not in use by Team 2005-02 because the information it provided was of limited utility or the RADAR was difficult to integrate.

- Team 2005-09

Team 2005-09 reported an unknown Eaton RADAR was in use by the team, but did not report the unknown Eaton RADAR was in use during the 2005 GCE ([52]), and later stated: "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). The author concluded the unknown Eaton RADAR was not in use by Team 2005-09 during the 2005 GCE. See paragraph V.C.34.b. The author considers it likely the unknown Eaton RADAR was not in use by Team 2005-09 because the information it provided was of limited utility or the RADAR was difficult to integrate.

VI.D.3. Use LIDAR sensors with capabilities similar to the SICK LMS 291 product family

There was a significant increase in the number of SICK LMS 291 product family LIDAR sensors in use by teams which participated in the 2004 or 2005 GCE from zero to 36[23]. See Table XLIII. The SICK LMS 291 product family has a feature the manufacturer referred to as "fog correction" ([75]). Although fog correction is a capability of other SICK LIDAR sensors in use by teams participating in the 2004 QID or GCE or 2005 GCE, such as the SICK LMS 211-30206 or 221-30206, the author proposes some combination of features, such as fog correction and price[24], of the SICK LMS 291 product family provides an explanation for the significant increase in the number of this specific sensor in use by teams participating in the 2005 GCE.