CHAPTER VII. NAVIGATION SENSOR INTEGRATION

VII.A. Discussion

During the comprehensive review of technical proposals for 2004 QID and GCE participants and review of technical proposals for 2005 GCE participants, the author noted an increase in the number of references to Kalman filtering from 2004 to 2005. The author attributed this to the difficulty teams had making sensor output available to the controlling intelligence, and concluded the use of a Kalman filter to integrate sensor output, in particular navigation sensor output, may have been a key factor.

VII.B. Analysis

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

In general, this was accomplished by searching team the published record for references to key words or substrings such as “kalman”, “filter”, “fusion”, “integrat” (e.g., integrate, integration, integrating, and integrated), “combin” (e.g., combine, combination, combining, and combined), and “navigat” (e.g., navigate, navigation, navigating, and navigated), and reviewing team responses to 2004 GCE SQ 1.c.2, 1.f.1, and 1.g.1 (see Table XXII), and 2005 GCE SQ 2.2.1, 2.3.2, and 2.4.3 (see Table XXIII).

- Team 2004-01

Team 2004-01 stated: “The Inertial sensing unit is based around a Motorola MCS6800 series MCU. The ISU collects inertial guidance data, carries out control orders from The [*sic*] AI/ NAV, and also collects and relays location and vehicle state information for use by the AI/ NAV.” ([8], p. 2). The author concluded Team 2004-01 independently implemented an other sensor fusion strategy.

- Team 2004-02

One AGNC Land Navigator was in use by Team 2004-02 during the 2004 QID and GCE. See Table XXVI. The author concluded the AGNC Land Navigator was a wrapper around the UNCUN1. See paragraph V.C.2.g. AGNC stated the following is a “feature” of the UNCUN1: “GPS and coremicro IMU integration providing precise position and attitude information between GPS updates and during GPS outages.” ([91]), but didn't identify the sensor fusion strategy used to integrate IMU and GPS output. The author concluded Team 2004-02 used a COTS component which implemented an other sensor fusion strategy.

- Team 2004-03

One unknown Crossbow IMU was in use by Team 2004-03 during the 2004 QID and GCE. See Table XXVI. As noted in paragraph V.C.3.e., at least five Crossbow products with different function and series designators have an integrated Kalman filter and either integrated GPS or GPS as an option ([96]). Although Crossbow has since discontinued products which were available at the time of the 2004 QID and GCE, the author considers is 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 Team 2004-03 used a COTS component which implemented a Kalman filter.

- Team 2004-04

One Smiths Aerospace North Finding Module was in use by Team 2004-04 during the 2004 QID and GCE. See Table XXVI. As noted in paragraph V.C.4.h., Smiths Aerospace has since been acquired by GE. The Smiths Aerospace North Finding Module provides a "GPS/Inertial Kalman Filter Solution" ([168]).

Team 2004-04 stated: "The GPS's are the only sensors onboard capable of calculating the geolocation of the vehicle. If the GPS signals drop out, the vehicle's global position becomes uncertain. To overcome this problem, the positioning filter algorithm will continue to calculate a global position during GPS outages by extrapolating a dead reckoning solution based on the shaft encoder and vehicle orientation sensor data. This will allow the vehicle to continue on course for a short period of time; however the solution will gradually drift and the accuracy of the position system will steadily decrease as long as the GPS outage continues. Eventually the error in the system will build up to the point where the vehicle can no longer continue on course with any confidence and the vehicle will have to stop and wait for a GPS reacquisition." ([44], p. 10).

The author considers it likely the "positioning filter algorithm" reported by Team 2004-04 was a feature of the Smiths Aerospace North Finding Module, and concluded Team 2004-04 used a COTS component which implemented a Kalman filter.

- Team 2004-05

Team 2004-05 stated: "Following a 'Sense-Model-Plan-Act' cycle, sensor data is gathered by SENSOR nodes and digested and/or filtered into a data product for communication to the SUPERVISOR node. This data is supplied to Model nodes (DRIVER and NAVIGATOR) for time-offset correction and integration into a pose estimate and environment model." ([45], p. 3). The author concluded Team 2004-05 independently implemented an other sensor fusion strategy.

- Team 2004-06

Team 2004-06 stated: "...one TMS2407 class [Digital Signal Processor] ... computes waypoint distance, direction, vehicle orientation, and dead reckoning." ([114], p. 1). The author concluded Team 2004-06 independently implemented an other sensor fusion strategy.

- Team 2004-07

Team 2004-07 stated: "The DGPS signal will be combined with 'dead reckoning' information from the inertial measurement unit and the axle encoder, and filtered by an Interacting Multiple Model estimator with two constant-velocity models with different levels of process noise." ([46], p. 8). The author concluded Team 2004-07 independently implemented an other sensor fusion strategy.

- Team 2004-08

One unknown Applanix POS LV was in use by Team 2004-08 during the 2004 QID. See Table XXVI. Applanix stated the POS LV is "fully integrated" ([120]), but did not identify the sensor fusion strategy in use. However, Teams 2004-10, 2005-13, and 2005-14 reported various Applanix sensors were in use which implemented a Kalman filter. The author concluded Team 2004-08 used a COTS component which implemented a Kalman filter.

- Team 2004-09

Team 2004-09 stated: "Sensor fusion also involves a combination of gyroscopic and horizon data to determine vehicle attitude." and "...GPS data is fused with image information in the planning units to assist in determining path selection and desired vehicle direction." ([47], p. 3). Via Figure 2 ("Basic Processing Structure") of the team technical proposal ([47], p. 3), Team 2004-09 reported various navigation sensors provide input into the "Master Planning Unit (MPU)". The author concluded Team 2004-09 independently implemented an other sensor fusion strategy.

- Team 2004-10

One unknown Applanix INS was in use by Team 2004-10 during the 2004 QID and GCE. See Table XXVI. Applanix stated the POS LV is "fully integrated" ([120]), but did not identify the sensor fusion strategy in use.

Team 2004-10 stated: "Applanix POS unit is utilized for inertial/GPS/DMI instrumentation. The Applanix POS system is a strapdown inertial navigation platform, featuring high-bandwidth, low-latency, Kalman filtering, GPS with azimuth measurement, distance measurement indicator (DMI)." ([77], p. 5). The author concluded Team 2004-10 used a COTS component which implemented a Kalman filter.

- Team 2004-11

Team 2004-11 stated: “The CPU’s function is to receive position and environment data from the other systems on board, to analyze the data, make route finding decisions, and to output control signals to the vehicle.” and “Most interpretation of sensor data will happen within the CPU and its associated program, although some minor tasks will be handled by the peripherals.” ([127], p. 3). Team 2004-11 identified “integration of the odometer and solid state magnetic compass” and “interpretation of GPS data” as functions of two “peripheral microcontrollers” ([127], p. 3). The author concluded Team 2004-11 independently implemented an other sensor fusion strategy.

- Team 2004-12

Team 2004-12 stated: “The vehicle handles GPS outages through a basic inertial and ground contact based velocity estimation algorithm. The vehicle receives acceleration data from the accelerometers (from which actual velocity is estimated), and speedometer and the wheel angle are continuously combined to provide an estimated position (after integration) of the vehicle.” ([129], p. 6). The author concluded Team 2004-12 independently implemented an other sensor fusion strategy.

- Team 2004-13

One Rockwell Collins GNP-10 was in use by Team 2004-13 during the 2004 QID and GCE. See Table XXVI. Team 2004-13 stated: “The primary geo-location system will be a Navcom differential GPS StarFire. [Team 2004-13] has chosen the StarFire SF-2050G. The output of this GPS will feed into the second navigation component, the Inertial Navigation System (INS). The INS will be supplied by Rockwell Collins. ... The INS will maintain, using MEMS based technology, an accurate position from the last known valid GPS fix.” ([132], p. 5).

Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE. See paragraph V.C.13. Teams 2004-13 and 2004-14 later stated: “An Extended Kalman Filter (EKF) was designed to fuse the inertial measurement unit (IMU) output – coming from a Rockwell Collins GNP-10 – with the GPS measurements from a Navcom Starfire DGPS system to provide high update rate measurements to the vehicle controller.” ([135], p. 4).

The author concluded Team 2004-13 independently implemented a Kalman filter.

- Team 2004-14

Team 2004-14 stated: “In the absence of GPS data due to communication outages the IND/DGPS [*sic*] system is aided by a 3D-magnetometer and the vehicle's odometer. The Kalman filter of the Navigation system continuously blends the INS/DGPS data with the odometer and magnetic compass.” ([134], p. 6).

Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE. See paragraph V.C.14. Teams 2004-13 and 2004-14 later stated: "An Extended Kalman Filter (EKF) was designed to fuse the inertial measurement unit (IMU) output – coming from a Rockwell Collins GNP-10 – with the GPS measurements from a Navcom Starfire DGPS system to provide high update rate measurements to the vehicle controller." ([135], p. 4).

The author concluded the "navigation system" referred to by Team 2004-14 was not in use during the 2004 QID and GCE, and that Team 2004-14 independently implemented a Kalman filter.

- Team 2004-15

Team 2004-15 stated: "[The challenge vehicle] NAV system will combine the info from the GPS and the integrating compass by using a Kalman filter." ([137], p. 4). The author concluded Team 2004-15 independently implemented a Kalman filter.

- Team 2004-16

Team 2004-16 stated: "Software integrates GPS/inertial/compass/pitch/yaw data for navigation. Sensor data are combined (inertial and GPS using Kalman filtering) and related to additional sensor data for accuracy." ([138]. p. 3). The author concluded Team 2004-16 independently implemented a Kalman filter.

- Team 2004-17

Team 2004-17 stated: "State estimation includes combined filtering from an inertial measurement unit (IMU), a magnetometer, and a DGPS unit to obtain position, heading and tilt angles." ([142], p. 5). The author concluded Team 2004-17 independently implemented an other sensor fusion strategy.

- Team 2004-18

One unknown ISI IMU was in use by Team 2004-18 during the 2004 QID and GCE. See Table XXVI. Team 2004-18 stated: "The output of the GPS will be combined with the INS system utilizing a Kalman filtering approach to geolocate the vehicle within the course." ([48], p. 6). Neither the RRS75 nor ISIS-IMU (see paragraph V.C.18.c.) implement a Kalman filter ([147] and [148]). The author concluded Team 2004-18 independently implemented a Kalman filter.

- Team 2004-19

Team 2004-19 stated: "The heading information, together with the speed of the wheels, combine to give high speed latitude-longitude position of the vehicle."; "This information is fused with the GPS data to correct the drift errors associated with the DRS."; "The data from the GPS unit is fused with the data from the dead reckoning system to both compensate for GPS outages and help correct GPS inaccuracies."; and "GPS outages and inaccuracies are compensated for by the dead reckoning system (DRS). 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). The author concluded Team 2004-19 independently implemented an other sensor fusion strategy.

- Team 2004-20

One unknown Crossbow INS was in use by Team 2004-20. See Table XXVI. Team 2004-20 stated: "INS and GPS data are combined to maintain both a position relative to recent positions for local navigation, and an absolute position for global navigation." ([107], p. 6).

All five products with AHRS and NAV (combined AHRS and GPS) function designators currently manufactured by Crossbow have an integrated Kalman filter ([96]). Although Crossbow has since discontinued products which were available at the time of the 2004 QID, the author considers it likely that multiple Crossbow AHRS sensors were available at the time of the 2004 QID, and concluded Team 2004-20 used a COTS component which implemented a Kalman filter.

- Team 2004-21

One Garmin GPS V was in use by Team 2004-21. No other navigation sensors were in use by Team 2004-21. See Table XXVI. Team 2004-21 stated: "We plan on making extensive use of the mapping data that is built in to the Garmin GPS V device. It is the only sensing device that will be directly interfaced into the main computer(s), and will form the backbone of our navigation system." ([155], p. 5). The author concluded Team 2004-21 did not implement a sensor fusion strategy.

- Team 2004-22

One unknown u-blox GPS receiver was in use by Team 2004-22 during the 2004 QID. See Table XXVI. Team 2004-22 stated: "...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).

As noted in paragraph V.C.22.g., at least three u-blox products with an integrated Kalman filter are currently available. The author considers is likely that multiple products with the capabilities reported by Team 2004-22 were available at the time of the 2004 QID, and concluded Team 2004-22 used a COTS component which implemented a Kalman filter.

- Team 2004-23

Team 2004-23 stated: “The vehicle receives and deals with all sensor data with the Surround Sensing/Sensor Fusion Module. This includes GPS data, and all external and all internal sensors except the cameras.” ([159], p. 10). The author concluded Team 2004-23 independently implemented an other sensor fusion strategy.

- Team 2004-24

Team 2004-24 stated: “The IMU data is combined with the GPS data within a 15 state Extended Kalman Filter (EKF) when both are present.” ([161], p. 4). The author concluded Team 2004-24 independently implemented a Kalman filter.

- Team 2004-25

Team 2004-25 stated: “The Challenge Vehicle uses a TALIN integrated DGPS/INS system from Honeywell for positioning. ... The integrated system uses Kalman filtering to provide precise position and velocity information at speeds up to 50 Hz.” ([49], p. 12). The author concluded Team 2004-25 used a COTS component which implemented a Kalman filter.

- Team 2005-01

One Northrop Grumman LN-270 was in use by Team 2005-01. See Table XXVIII. A similar Northrop Grumman INS uses a Kalman filter ([223]), but Northrop Grumman did not report the LN-270 has an integrated Kalman filter ([224]). The author concluded Team 2005-01 used a COTS component which implemented an other sensor fusion strategy.

- Team 2005-02

One Smiths Aerospace North Finding Module was in use by Team 2005-02. See Table XXVIII. As noted in paragraph V.C.27.d., Smiths Aerospace has since been acquired by GE. The North Finding Module provides a “GPS/Inertial Kalman Filter Solution” ([168]). The author concluded Team 2005-02 used a COTS component which implemented a Kalman filter.

- Team 2005-03

In response to 2005 SQ 2.4.3 (see Table XXIII), Team 2005-03 stated: “This is all integrated at a C6000 DSP chip as described in section 2.3.4.” ([33], p. 11). In response to 2005 SQ 2.3.4 (see Table XXIII), Team 2005-03 described a sensor integration solution. The author concluded Team 2005-03 independently implemented an other sensor fusion strategy.

- Team 2005-04

Team 2005-04 stated: “Localization, vehicle motion status, and internal state sensing is accomplished using the Novatel GPS with Omnistar HP differential corrections, the Crossbow IMU, wheel speed sensors that were added to the vehicle, engine speed measurements, and brake and throttle position information. These sensors are monitored for changes in their operating state, validated using both dynamic and rule based tests, and finally fused using a Kalman filter based approach to provide continuous position and orientation information even [*sic*] the presence of individual sensor dropouts, reduced accuracies, or complete failures.” ([169], p. 11). The author concluded Team 2005-04 independently implemented a Kalman filter.

- Team 2005-05

One Systron Donner C-MIGITS III was in use by Team 2005-05. See Table XXVIII. An “Optimized 28-State Kalman Filtered Navigation Solution” is a feature of the Systron Donner C-MIGITS III ([225]). The author concluded Team 2005-05 used a COTS component which implemented a Kalman filter.

- Team 2005-06

One Oxford RT3000 was in use by Team 2005-06. See Table XXVIII. A Kalman filter is a feature of the Oxford RT3000 ([226]). The author concluded Team 2005-06 used a COTS component which implemented a Kalman filter.

- Team 2005-07

The author estimated one unknown GPS receiver was in use by Team 2005-07. See Table XXVIII. Team 2005-07 stated: “The key to [Team 2005-07's] approach is a software architecture that allows us to integrate the sensor technology from multiple sensors into single vehicle control signals at real-time speeds. This architecture, MURE, or Mobile Unmanned Robotics Environment, enables us to combine location, terrain data, and real time sensor data with minimum processing and power requirements.” ([118]). The author concluded Team 2005-07 independently implemented an other sensor fusion strategy.

- Team 2005-08

One Honeywell TALIN-5000 was in use by Team 2005-08. See Table XXVIII. Team 2005-08 stated: “A Honeywell TALIN 5000 Inertial Navigator Unit provides a blended navigation solution at a 50Hz update rate. This solution incorporates DGPS data from the NovAtel unit, true groundspeed from a Vansco Doppler radar sensor, and internal acceleration and rotation data from precision accelerometers and a 3-axis ring laser gyro subsystem combined in an internal kalman filter.” ([173], p. 8). The author concluded Team 2005-08 used a COTS component which implemented a Kalman filter.

- Team 2005-09

Team 2005-09 stated: “Localization is accomplished by fusing input from multiple GPS units, a magnetic compass, inertial navigation system, and several shaft encoders. Two Trimble GPS systems provide sub-meter accuracy through an Omnistar subscription. The Trimble GPS units are used primarily by the agriculture community for autonomous field preparation and harvesting. A third GPS is provided by a MIDG-2 inertial navigation system that comes from the remote controlled plane community. This GPS unit is augmented by an internal Inertial Measurement Unit that maintains location during GPS outages. In addition, a Honeywell magnetic compass is used as an alternative source of heading. Additionally, shaft encoders provide odometry at very slow speeds providing information that is needed for dead reckoning.” ([175], p. 7). The author concluded Team 2005-09 independently implemented an other sensor fusion strategy.

- Team 2005-10

One unknown Kearfott INS was in use by Team 2005-10. See Table XXVIII. A “multi-state Kalman filter” is a feature of the Kearfott MILNAV product family ([181]). The author concluded Team 2005-10 used a COTS component which implemented a Kalman filter.

- Team 2005-11

One unknown Crossbow INS was in use by Team 2005-11. See Table XXVIII. Team 2005-11 stated: “The Crossbow NAHRS blends GPS, magnetometer and accelerometer measurements into an Extended Kalman Filter (EKF) algorithm.” ([182], p. 7). The author concluded Team 2005-11 used a COTS component which implemented a Kalman filter.

- Team 2005-12

One unknown Trimble DGPS receiver was in use by Team 2005-12. See Table XXVIII. Team 2005-12 stated: “Dead reckoning, based on front-wheel ABS sensors and steering wheel position, interpolates position between GPS updates and during GPS outages. A Kalman filter optimally combines the two measurements each time a GPS position is received.” ([185], p. 5). The author concluded Team 2005-12 independently implemented a Kalman filter.

- Teams 2005-13 and 2005-14

One unknown Applanix INS was in use by Teams 2005-13 and 2005-14. See Table XXVIII. Teams 2005-13 and 2005-14 stated: “[The challenge vehicle] estimates 6-axis pose, velocity and acceleration (latitude, longitude, altitude, roll, pitch, yaw) by combining inertial sensing, GPS data and odometry using a Kalman filter.” ([11], p. 7 and

[12], p. 7). Teams 2005-13 and 2005-14 later stated: “The [unknown Applanix INS] provides position estimates by fusing inertial and differential GPS position estimates through a Kalman filter.” ([24], p. 478). The author concluded Teams 2005-13 and 2005-14 used COTS components which implemented a Kalman filter.

- Team 2005-15

Team 2005-15 reported one unknown NavCom DGPS receiver, unknown Rockwell Collins IMU, PNI TCM2, and OEM speedometer encoder were in use by the team. See Table XXVIII. Team 2005-15 stated: “A Kalman filter fuses these data streams into an estimate of the actual location, heading, and velocity.” ([53], p. 9). The author concluded Team 2005-15 independently implemented a Kalman filter.

- Team 2005-16

Team 2005-16 stated: “[The challenge vehicle] achieves its localization through an unscented Kalman filter (UKF)...” ([195], p. 5). The author concluded Team 2005-16 independently implemented a Kalman filter.

- Team 2005-17

One Oxford RT3102 was in use by Team 2005-17. See Table XXVIII. A Kalman filter is a feature of the Oxford RT3102 ([226]). The author concluded Team 2005-17 used a COTS component which implemented a Kalman filter.

- Team 2005-18

Team 2005-18 reported one NovAtel DL-4plus, NavCom SF-2050G, and Northrop Grumman LN-200 were in use by the team. See Table XXVIII. Team 2005-18 stated: “The inputs from these sensors are combined through Kalman filtering to produce an optimal estimation of state.” ([197], p. 9). The author concluded Team 2005-18 independently implemented a Kalman filter.

- Team 2005-19

Team 2005-19 reported one Northrop Grumman LN-200, Trimble AgGPS 252, and unknown speed brake sensor were in use by the team. See Table XXVIII. Team 2005-19 stated: “...[Team 2005-19] fuses three sensors into a smooth Bayesian optimal estimate of the vehicle’s position and attitude... These three sensors are combined to estimate a fifteen element vehicle state: x, y, z position and velocity, a bias on each accelerometer, vehicle yaw, pitch, and roll, and a bias on each rate gyro.” ([55], p. 4).

Team 2005-19 later stated: “The three sensors ... are fused into an estimate of [the challenge vehicle's] position, velocity, and attitude using an extended Kalman Filter (EKF).” ([54], p. 631).

The author concluded Team 2005-19 independently implemented a Kalman filter.

- Team 2005-20

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. This system combines GPS and inertial functionality to provide uninterrupted operation with highly accurate position and attitude measurements. It is augmented with Differential Global Positioning System (DGPS) receivers to provide corrections when in coverage. The system can provide high accuracy position (10cm) and heading at operating speeds of 20 Hz[.]" ([56], pp. 8 - 9).

However, Team 2005-20 also stated: "In motion, 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 Team 2005-20 used a COTS component which implemented an other sensor fusion strategy.

- Team 2005-21

Two Oxford RT3100s were in use by Team 2005-21. See Table XXVIII. A Kalman filter is a feature of the Oxford RT3100 ([226]). The author concluded Team 2005-21 used COTS components which implemented a Kalman filter.

- Teams 2005-22 and 2005-23

A NovAtel ProPak-LBplus and NovAtel HG1700 SPAN were in use by Teams 2005-22 and 2005-23. See Table XXVIII. NovAtel stated: "IMU measurements are used by the GNSS/INS receiver to compute a blended GNSS/INS position, velocity and attitude solution at up to 100 Hz." ([227]), but did not describe how sensor fusion was implemented. The author concluded Teams 2005-22 and 2005-23 used COTS components which implemented an other sensor fusion strategy.

VII.C. Results

Results are presented in Tables XLIV, XLV, and XLVI, and summarized in Tables XLVII, XLVIII, XLIX, L, LI, and LII.

VII.C.1. Differences in the number of teams utilizing a COTS component to integrate navigation sensors from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 and 2005 GCE (see Table XLVII):

- There was an increase in the number of teams utilizing a COTS component to integrate navigation sensors from 33.3 percent to 60.9 percent, a difference of 27.6 percent.

- There was a corresponding decrease in the number of teams which independently implemented a sensor fusion strategy.

As a percentage of the total number of teams which participated in both the 2004 and 2005 GCE (see Table L):

- There was an increase in the number of teams utilizing a COTS component to integrate navigation sensors from 41.7 percent to 66.7 percent, a difference of 25.0 percent.

- There was a corresponding decrease in the number of teams which independently implemented a sensor fusion strategy.

VII.C.2. Differences in the number of teams utilizing a COTS component which implemented a Kalman filter or independently implementing a Kalman filter from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 and 2005 GCE (see Table XLVIII):

- There was an increase in the number of teams utilizing a COTS component which implemented a Kalman filter or independently implementing a Kalman filter to integrate navigation sensors from 60.0 percent to 69.6 percent, a difference of 9.6 percent.

As a percentage of the total number of teams which participated in both the 2004 and 2005 GCE (see Table LI):

- There was no change in the number of teams utilizing a COTS component which implemented a Kalman filter or independently implementing a Kalman filter to integrate navigation sensors.

VII.C.3. Differences in the number of teams utilizing a COTS component which implemented a Kalman filter from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 and 2005 GCE (see Table XLIX):

- There was an increase in the number of teams utilizing a COTS component which implemented a Kalman filter to integrate navigation sensors from 26.6 percent to 43.5 percent, a difference of 16.9 percent.

As a percentage of the total number of teams which participated in both the 2004 and 2005 GCE (see Table LII):

- There was an increase in the number of teams utilizing a COTS component which implemented a Kalman filter to integrate navigation sensors from 33.3 percent to 41.7 percent, a difference of 8.4 percent.

VII.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 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 the 2004 and 2005 GCE, in general.

Overall, the author concluded the use of a COTS component to integrate navigation sensors was an example of reducing complexity, and that teams which independently implemented an other sensor fusion strategy diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge to attempt to solve a problem that had been solved by providers of COTS components at the time of the 2004 and 2005 GCE, not a problem of artificial intelligence, and were, in effect, solving a wrong problem. See paragraph XIV.A.3.

VII.D.1. Use a COTS component to integrate navigation sensors

The author concluded the use of a COTS component to integrate navigation sensors was a key factor. COTS components combined navigation sensor output, such as heading, roll, pitch, and yaw, axle rotation, or geolocation information. The author asserts COTS components were more mature and the results more reliable than independently implemented solutions.

In addition, many teams reported the challenge vehicle controlling intelligence was constrained from entering “out-of-bounds areas” by algorithmically or manually classifying these areas as impassable terrain. However, a controlling intelligence which was unable to accurately locate itself could not determine if it was in impassable terrain. Inaccurate geolocation information, specifically GPS sensor failure, was directly implicated in the failure of five teams to complete the 2005 GCE. See paragraph XIV.D.3.b.

The author proposes this may explain the increase in the use of COTS components which provide more reliable geolocation information to the controlling intelligence.

- One of four teams which successfully completed the 2005 GCE, and one of five teams which completed the 2005 GCE course, independently implemented a navigation sensor integration strategy: Team 2005-16. Team 2005-16 had prior experience and significant corporate and academic sponsorship. See Chapter X. The other three teams which successfully completed the 2005 GCE, and other four teams which completed the 2005 GCE course, used a COTS component.

- Counting 2005 GCE co-participants, one of which participated in the 2004 GCE (Teams 2005-13 and 2005-14 and Teams 2005-22 and 2005-23), eight of the nine teams which completed more than 25 percent of the 2005 GCE course (32.9 miles) used a COTS component to integrate navigation sensors.

- Thirteen of 21 teams which participated in the 2005 GCE and which used a COTS component to integrate navigation sensors completed more than 7.4 miles of the 2005 GCE course, more than the maximum number of miles completed by any team which participated in the 2004 GCE.

Alternately, the author concluded the decrease in the number of teams which independently implemented a sensor integration strategy from 2004 to 2005 was a contributing factor to the increase in the average number of miles of the 2005 GCE course teams completed.

- With the exception of Team 2005-16, above, no team which independently implemented a navigation sensor integration strategy completed more than 25 percent of the 2005 GCE course.

VII.D.2. Use a Kalman filter to integrate navigation sensors

The author concluded the use of a Kalman filter to integrate navigation sensors was a key factor.

- One of four teams which successfully completed the 2005 GCE, and one of five teams which completed the 2005 GCE course, independently implemented a Kalman filter: Team 2005-16. Team 2005-16 had prior experience and significant corporate and academic sponsorship. See Chapter X. The other three teams which successfully completed the 2005 GCE, and other four teams which completed the 2005 GCE course, used a COTS component which implemented a Kalman filter.

- Counting 2005 GCE co-participants, one of which participated in the 2004 GCE (Teams 2005-13 and 2005-14 and Teams 2005-22 and 2005-23), five of the nine teams which completed more than 25 percent of the 2005 GCE course (32.9 miles) used a Kalman filter to integrate navigation sensors.

- Fifteen of 21 teams which participated in the 2005 GCE and which used a Kalman filter to integrate navigation sensors completed more than 7.4 miles of the 2005 GCE course, more than the maximum number of miles completed by any team which participated in the 2004 GCE.

Alternately, the author concluded the decrease in the number of teams which independently implemented a sensor integration strategy from 2004 to 2005 was a contributing factor to the increase in the average number of miles of the 2005 GCE course teams completed.

- With the exception of Team 2005-16, above, no team which independently implemented a Kalman filter completed more than 25 percent of the 2005 GCE course.