CHAPTER XI. PRE-MAPPING

XI.A. Discussion

Many teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team. "Pre-mapping" is defined herein as the addition of metadata as an "overlay" to existing map data which allowed team members to constrain the decisions of the challenge vehicle controlling intelligence. The combination or fusion of map data from multiple maps into a single map is not considered to be pre-mapping, although it was a necessary prerequisite for pre-mapping as defined to by the author when multiple maps were in use by a team. Team strategies to increase waypoint density are considered path editing, and are discussed in Chapter XII.

XI.B. Analysis

Team 2004-10 completed 7.4 miles of the 2004 GCE course, the greatest number of miles completed by any team. Team 2004-10 reported the team performed extensive pre-mapping in the two hours between receiving the 2004 GCE RDDF and the first Departure Signal. Based on the strength of Team 2004-10's performance during the 2004 GCE, the author reviewed the published record to determine whether pre-mapping provided a competitive advantage to teams which participated in the 2004 QID or GCE or 2005 GCE and which reported pre-mapping was in use. Several teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team. For example:

- Team 2004-07

  In response to 2004 SQ 1.d.1 (see Table XXII), Team 2004-07 stated ([46], p. 6):

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  Prior to the race we will create annotated maps of the
  Southern California/Nevada region based on our own GPS
  measurements and on USGS Digital Raster Graphics with
  1-meter resolution, USGS Digital Elevation Models with
  30-meter resolution, and US Census Bureau Tiger 2000
  Transportation Layers including roads from U.S.
  highways to vehicular trails, for all regions for
  which these files are available from the California
  Spatial Information Library and the W.M. Keck Earth
  Sciences and Mining Research Information Center.

  We will annotate areas and road arcs on these maps
  with subjectively determined cost information and
  store the resulting cost maps in a multiresolution
  data structure...
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- Team 2004-10

Team 2004-10 stated: “An off-board map database contains map features including sand, water, paved roads, unpaved roads, vegetation, rock, dry lake beds, out of bounds, and non-traversable terrain to the extent that they are known. This data comes from integrated USGS and BLM maps and is corrected relative to aerial imagery and road reconnaissance. During the two hour period prior to race, provided waypoints are used to extract relevant portions of this map database, which is transferred to vehicle...” ([77], pp. 3 - 4).

- Team 2004-17

Team 2004-17 stated: “We have obtained 1m resolution images of the entire possible race-course, minus censored data over military bases. The computer alone will not know what to do with the RGB maps, so we will 'paint' terrain types onto the maps. Based on color pixel value the computer will be able to distinguish roads, railroad tracks, overpasses, water, mountains, buildings, dry lakes, vegetation areas, and off-road trails.” ([142], p. 6).

- Team 2004-18

Team 2004-18 stated: “The map data will be processed prior to the race to determine zones that will exceed safe operating parameters of the vehicle.” ([48], p. 3), “Pre-processed data consists of map data, boundaries, hydrology, and elevations.” ([48], p. 4), and “Map data will be acquired from the USGS for the southern California and Nevada regions. These maps will consist of 1:24,000 scale DEMs (Digital Elevation Models) and DLGs (Digital Line Graphs). The accuracy of these maps is 40 ft. These digital maps will be analyzed with commercial and custom developed software to determine zones that the vehicle will not be able to traverse due to steep slopes, deep water, etc. Road, bridge, and stream locations will also be stored for use in path planning and object detection and classification while the vehicle is in motion. All map data will be pre-stored on the vehicle for two purposes: high risk long distance route planning once the GPS waypoints are given to us and predictive information during dynamic operation. For instance, if it is known that a stream is within a certain 40ft region then the software interpreting the sensor data will place a higher likelihood on the determination of finding water in the region and the object will be correctly detected and classified according to known depth from the pre-stored map data.” ([48], p. 4).

- Team 2004-19

Team 2004-19 stated: “The maps will be preprocessed within the 2 hours before the race by members of [Team 2004-19] to eliminate areas which are out of bounds (as defined by the RDDF). Further areas will be eliminated as possible route segments at the discretion of [Team 2004-19]. This is to prevent the vehicle from entering an area of treacherous terrain if possible.” ([151], p. 2).

- Team 2004-23

Team 2004-23 stated: “There will be three types of maps. The first is the basic map of the area from the USGS data library, supplied by the OSU Mapping Center. This is being manually 'weighted' to assign hospitability-weights based on photographic images and other known information and create the Hospitability Map.” ([159], p. 7).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “An off-board route planning system incorporates elevation topology, satellite imagery and drive-by topography data. The map data is sparse relative to the possible GC routes. The planning process designates contexts like paved road, dirt trail or underpass. The race planners refine a preplanned route and set intended speeds compliant to the race data definition file. Just prior to race start [the challenge vehicle] receives a path definition file (PDF) consisting of [waypoints], coordinates, speeds and contexts defined for every meter along the race route.” ([11], p. 7 and [12], p. 7).

- Team 2005-21

Team 2005-21 reported a complex description of a three-stage “Pre-Mission Route Planner” and stated: “In the third stage on race day, each split route will be handed over to a human editor for review and possible editing. The editor will then assess his/her assigned split route and look for potential problems with the help of the in-house developed visualization/editing software. The vertical profile at the vicinity of each waypoint being examined is shown to alert him/her of potential speed problems. Maximum vehicle speed at each waypoint can be specified... In case of doubt over the terrain contour from sometimes-ambiguous geo image, the editor can then switch to a 3D exocentric view mode from the map view mode, to determine whether significant terrain drop or rise occur at the side of the route.” ([160], p. 12).

XI.C. Results

- Nine of 48 teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team: Teams 2004-07, 2004-10, 2004-17, 2004-18, 2004-19, 2004-23, 2005-13, 2005-14, and 2005-21.

- Ten of 48 teams which participated in the 2004 QID or GCE or 2005 GCE explicitly stated no external map data was in use by the team: Teams 2004-11, 2004-12, 2004-24, 2005-03, 2005-09, 2005-10, 2005-12, 2005-20, 2005-22, and 2005-23.

- Eleven of 48 teams did not report external map data was in use, but did not explicitly state no external map data was in use by the team: Teams 2004-04, 2004-05, 2004-06, 2005-02, 2005-04, 2005-06, 2005-08, 2005-15, 2005-16, 2005-17, and 2005-18.

- Most[26] other teams reported external map data was in use by the team, but did not report pre-mapping was in use.

In addition, of the 12 teams which participated in both the 2004 and 2005 GCE:

- Two teams reported pre-mapping was in use during both the 2004 and 2005 GCE: Teams 2004-10 and 2005-13 and 2004-23 and 2005-21. Team 2005-13 successfully completed the 2005 GCE. Team 2005-21 completed the 2005 GCE course, but was not successful.

- One team reported external map data was in use during the 2004 and 2005 GCE, but did not report pre-mapping was in use: Team 2004-02 and 2005-01.

- Seven teams reported external map data was in use during the 2004 GCE, but explicitly stated external map data was not in use, or did not report external map data was in use, during the 2005 GCE: Teams 2004-07 and 2005-05, 2004-08 and 2005-07, 2004-13 and 2005-15, 2004-16 and 2005-17, 2004-17 and 2005-18, 2004-18 and 2005-20, and 2004-25 and 2005-22.

- Insufficient technical detail was reported by Teams 2004-04 and 2005-02 and 2004-06 and 2005-03 to determine if external map data was in use during the 2004 GCE or if there was a change in strategy between the 2004 and 2005 GCE.

Two of the teams which reported external map data was not in use by the team successfully completed the 2005 GCE: Teams 2005-06 and 2005-16.

Team 2005-06 later stated: "The rules did not prevent normalization of DARPA's data before they were fed to the vehicles, neither did they prevent elevation map databases, however, [the challenge vehicle] did not make use of any information other than its sensor readings and DARPA's waypoint data given to it in raw form." ([28], p. 510).

Team 2005-16 did not report external map data was in use by either the team technical proposal ([195]) or results published via the Journal of Field Robotics ([25]).

XI.D. Conclusions

Although two of the four teams which successfully completed the 2005 GCE (Teams 2005-13 and 2005-14) reported pre-mapping was in use, two of the four teams did not report pre-mapping was in use. As a result, the author concluded it was possible to successfully complete the 2005 GCE without the use of pre-mapping, and that pre-mapping was not a key factor.

Teams 2005-13 and 2005-14 stated: “Much of the technical approach described in this paper was excessive given the final form of the Grand Challenge. The groomed roads and carefully detailed route provided by the organizers greatly reduced two of the competitive advantages (namely the H1 & HMMWV chassis and the preplanning system) applied by the team.” ([24], p. 505).

The author considers this supports a conclusion that the pre-mapping in use by Teams 2005-13 and 2005-14 did not provide a competitive advantage to the teams, but that insufficient evidence was available to conclude pre-mapping was a negative selector.

However, the author concluded pre-mapping may address certain vulnerabilities reported by teams participating in the 2004 QID or GCE or 2005 GCE: terrain features indicative of the presence of water and significant changes in elevation.

XI.D.1. Terrain features indicative of the presence of water

Teams 2004-05 and 2004-20 reported the implementation of certain sensors or types of sensors to enable the challenge vehicle to detect and avoid water obstacles, such as “depth finders”, “conductivity sensors”, and “water sensors”. See Table XXV. No team participating in the 2005 GCE reported similar sensors were in use. See Table XXVII. Team 2004-18 specifically reported using pre-mapping to identify areas where the challenge vehicle controlling intelligence might encounter “deep water”, although Team 2004-18 did not report implementing sensors to detect and avoid water obstacles. See paragraph XI.B.

The 2004 and 2005 GCE courses were located in the Mojave Desert. There are few permanent water features in the area of the Mojave Desert on which the 2004 and 2005 GCE courses were located. As a result, the author concluded team implementation of these sensors increased complexity and was unlikely to have had an effect on success.

However, the temporary presence of water in the Mojave is accompanied by washouts, dry lake beds, and gullies, of which the challenge vehicle controlling intelligence should be aware and which had a very real impact on team success during the 2005 GCE. Following the 2005 GCE Team 2005-06 stated: “...the director of DARPA said later that if we hadn't had a bug where we slowed down in the dry lakebeds, we would have either beaten [Team 2005-16] or been very, very close to [Team 2005-16's] car. The bug meant we went from 30 miles an hour to two miles an hour on all the dry lakebeds. We'd never tested in an area 100 feet wide like that. We call it the $2 million bug.” ([31]).

The author notes the 2004 and 2005 GCE RDDF define several areas with extreme lateral boundary offset. See paragraph II.C.7.d. Although the author cannot be certain, these areas were probably the dry lake beds reported by Team 2005-06. As a result, although the author acknowledges pre-mapping may have offered a solution to this problem, the author asserts pre-mapping would not have addressed the root cause of the problem. The root cause of the problem reported by Team 2005-06 was inadequate test and evaluation. If Team 2005-06 had tested in areas with extreme lateral boundary offset, as indicated by the 2004 GCE RDDF to which it had access prior to the 2005 GCE, it may have encountered the "$2 million bug" and subsequently won the 2005 GCE.

XI.D.2. Significant changes in elevation

Several teams reported the use of ultrasonic or other sensors to provide the challenge vehicle controlling intelligence with the ability to detect rapid changes in elevation. For example:

- Team 2004-20

Team 2004-20 stated: "In addition, there are narrow-angle sonars pointing down ahead of each leading wheel and behind each trailing wheel. These are used to check supporting terrain during low-speed operation." ([107], p. 5).

- Team 2005-01

Team 2005-01 stated: "Cliffs are a serious issue that [Team 2005-01] has encountered, for cliffs generally imply wide open space, which is typically a safe place to drive. [Team 2005-01] will meet this challenge by adjusting its LADAR sensors over the side of the vehicle, to detect and avoid the cliffs." ([10], p. 13).

- Team 2005-04

Team 2005-04 stated: "Two additional ultrasonic rangefinders are mounted high on the front of the vehicle and angled downward, in an attempt to detect sharp dropoffs on either side of the vehicle." ([169], p. 9).

Other teams reported the use of pre-mapping or external map data to eliminate areas with significant changes in elevation from consideration. For example:

- Team 2004-07

Team 2004-07 reported pre-mapping was in use by the team. See paragraph XI.B. In response to 2004 SQ 1.g.3 (see Table XXII), Team 2004-07 stated: "Challenge Route boundaries are treated in the same way as cliffs or any other known impassable obstacle that may not be detectable by onboard sensors." ([46], p. 8).

- Team 2004-19

Team 2004-19 reported pre-mapping was in use by the team to eliminate areas of "treacherous terrain" from consideration. See paragraph XI.B.

- Team 2004-25

Team 2004-25 stated: "Impassable routes such as lakes, cliffs, and areas outside the allowable boundaries will also be removed from the database of possible solutions." ([49], p. 8).

- Team 2005-19

Team 2005-19 stated: "[The challenge vehicle] also makes use of digital elevation models (DEMs) provided by Digital Globe to initialize its maps. The DEMs have errors less than 10m, and can be used to detect roads and large negative obstacles like cliffs. At the beginning of the race, this map data is used as low confidence sensor data to plan an initial path from the start line to the finish." ([55], p. 6).

- Team 2005-21

Team 2005-21 reported pre-mapping was in use by the team to eliminate areas with significant changes in elevation from consideration. See paragraph XI.B.

Although no challenge vehicle was destroyed during the 2004 or 2005 GCE, the author concluded the decision to use pre-mapping to eliminate areas with significant changes in elevation from consideration by the challenge vehicle controlling intelligence was nonetheless prudent due to the high cost of team challenge vehicles, and considers this validates the decisions by some teams to perform pre-mapping for this purpose.

XI.D.3. External map data

Seven of the 12 teams which participated in both the 2004 and 2005 GCE reported external map data was in use during the 2004 GCE, but explicitly stated external map data was not in use, or did not report external map data was in use, during the 2005 GCE. On average, these teams completed 48.6 miles of the 2005 GCE course, approximately 25 times the average distance completed by teams during the 2004 GCE and approximately six and one-half times the greatest distance traveled by Team 2004-10 during the 2004 GCE of 7.4 miles.

The author does not consider the increase in the average number of miles of the 2005 GCE course which were completed to be due to the decrease in the number of teams which explicitly stated external map data was not in use, or did not report external map data was in use, during the 2005 GCE. However, the author concluded the use of external map data during the 2004 GCE may have required teams to implement overly-complex solutions to the problem of autonomous navigation, and may, in fact, have been a "wrong problem" solved by some teams which diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge. See paragraph XIV.A.4.