Preplanning for high performance autonomous traverse of desert terrain exploiting a priori knowledge to optimize speeds and to detail paths

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Abstract

Good human drivers adjust radii, favor lanes and inherently set speeds while racing. They gracefully enter and exit turns, and "read the terrain" or use foreknowledge of the course to slow down for harsh terrain features. Robots do not yet do this without the benefit of preplanning. This paper describes technologies and methodologies for preplanning including: path detailing, speed setting, terrain knowledge, and verification.

The result of preplanning is the generation of two high performance, successful routes for two autonomous robots in the 2005 Grand Challenge traverse of 132 miles in about 7 hours.
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3 Introduction

Pre-planning is the creation of a path, including its associated speeds and estimated elapsed time, prior to driving a route. The preplanning system incorporates aspects common to mission scaled schedulers and planners for space missions [1][2]. It provides the critical input that allows the navigation system to make assumptions about the world it is operating in. Done well, it increases the overall capability and robustness of the navigation system. It helps a robot by allowing it anticipate and slow down for obstacles and conditions without sensing them directly. Good human drivers adjust radii, favor lanes and inherently set speeds. They gracefully enter and exit turns, and "read the terrain" or use foreknowledge of the course to slow down for harsh terrain features. Robots do not yet do this without the benefit of preplanning.

The context of the constrained environment is the 2005 Grand Challenge. In the Grand Challenge, competitors were required to traverse up to 175 miles of desert terrain in less than 10 hours, where the actual route was unknown until 2 hours before the start. In the Grand Challenge, the competitors Stanford, Oshkosh, and Ensco are known to have taken advantage of preplanning. The preplanning used allowed them to review the route, and check for any part of it that would be non-nominal. In addition, Stanford and Oshkosh further “smoothed” the route by increasing the number of waypoints beyond the coarse number as originally given by the race organizers. Stanford’s method of smoothing the route was to employ a conjugant gradient algorithm to optimize between turning radius and distance from the centerline [3]. This method, combined with the ability to cap speeds allowed them to quickly produce a route on race morning.
As detailed above in Figure 1, the Red Team approach to preplanning involves the initial generation of a path using splines to smooth an initially coarse list of waypoints. The smoothed path is then modified by human editors to widen turns, and identify high risk areas in the path. In parallel, risk is assessed throughout the course and an automated speed setter uses this information to achieve a desired elapsed time. This resulting path is then output in the form of a series of fine waypoints which are used by the robot to traverse the course. As part of this process, several rounds of verification are performed, to find and remove any problems with the path. Periodically the current best path is transferred to the robot to ensure that there is always a route available, in case of some unexpected failure.

Path detailing is a human edited process while speed setting and verification use a combination of human and automated processes. The path generated by the process is then downloaded to a robot and used onboard as a seed for onboard navigation.

Human editors are used to perform feature extraction that is beyond the state-of-the-art in automated image understanding. Current state of the art in image extraction is limited to items such as road extraction from imagery [4] and object detection and delimiting [5] for large scale features such as buildings. While delimiting and detecting objects would be useful to identify underpasses, overpasses and potentially gates both of the referenced approaches are only semi-automated, requiring human editors to intervene for specific features. Even if these technologies were implemented, they would still not account for obstacles such as road washouts which would be potentially fatal to the robot.
The following sections describe path detailing, speed setting, the use of terrain data, and the verification process.

4 Path Detailing

Path detailing is a process that transforms a set of coarse waypoints and speed limits to a preplanned path with one meter spaced waypoints. The resulting path defines location and speed, and is a smooth trajectory for robots to follow with the goal of increasing the probability of successfully navigating a route.

As part of this process a smooth path is generated by interpolating between an initial set of coarse waypoints using splines. The splines can then be adjusted by human editors to smooth tight radius curves and to bias the path away from areas of high risk. The splines are then converted to one meter spaced waypoints that are followed by the vehicles.

The interpolation process produces a route of curved splines from waypoint to waypoint defined by a series of control points and spline angle vectors. Human editors can alter splines by shifting a series of spline control points, and spline angle vectors that adjust to specify the location and orientation of a path. The generated splines are constrained to ensure continuity to the second order which prevents discontinuities in both the position and heading of a path.

4.1 Human Editing

The human editing process helps eliminate unnecessary curvature which in turn helps robots drive more predictably. Smooth paths are also generally faster since decreasing the amount of curvature in a path reduces concerns for dynamic roll-over and side slip.

To do this, human editors can move spline control points to adjust the location and radius for route segments between waypoints. This allows editors to bias the vehicle away from, or slow down for, dangerous terrain features. Figure 1 shows an instance where an editor has widened a turning radius in a path. This type of editing helps to reduce the likelihood of a robot performing a 3-point turn, and thus makes the path faster.
5 Speed Setting

During pre-planning, a speed setting process specifies the target speeds for an autonomous vehicle given a target elapsed time to complete a preplanned path. Speed setting is performed by assessing the risk for a given robot to traverse a section of terrain based on available information. An automated process then uses a speed policy generated by combining the risk assessment with any speed limits imposed on the course to assign speeds to each waypoint in the path.

5.1 Risk Assignment

Risk estimation discretizes risk into four levels (dangerous, moderate, safe and very safe) in classifying terrain. Each risk level maps to a range of safe robot driving speeds. Risk is first assigned regionally, over multi-kilometer scale distances, using general characteristic of the terrain under consideration. Once the
entire route has risk assigned at a coarse level, a first order approximation of the ease/difficulty of that route, as well as an estimate of the overall elapsed time can be generated. Speeds used for each risk level during the 2005 Grand Challenge are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Sandstorm</th>
<th>Highlander</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Risk</td>
<td>5 m/s</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Medium Risk</td>
<td>7.5 m/s</td>
<td>7-9 m/s</td>
</tr>
<tr>
<td>Low Risk</td>
<td>10-10.5 m/s</td>
<td>10-12 m/s</td>
</tr>
<tr>
<td>Very Low Risk</td>
<td>12 m/s</td>
<td>13-13.5 m/s</td>
</tr>
<tr>
<td>Target Time</td>
<td>7hrs 02m</td>
<td>6hrs 19m 40s</td>
</tr>
</tbody>
</table>

Table 1: Speeds for various risk categories

In addition to classifying risk at a macro level, risk is also assigned to local features of importance. This processing step characterizes and slows the path down for washouts, overpasses, underpasses, and gates. In this way the human editor provides a robot with a set of “pace notes,” similar to the information used by professional rally race drivers. These details allow a robot to take advantage of prior knowledge of the world to slow preemptively, much as a real world driver would slow down. This is a critical part of the process for increasing the robustness of the onboard navigation system.

5.2 Specifying an Elapsed Time

An automated process combines the risk assessment with a dynamics model of the robot and speed limits to generate a path that achieves a given elapsed time. In the first step of the process, each waypoint is assigned the lesser of the speed limit and the dynamics-safe speed. The resulting path is then filtered to provide reasonable acceleration and deceleration profiles, using the same algorithms as the onboard navigation system. This results in the fastest permissible path.

Next, the speed policy generated during the risk assessment is applied to the waypoints and the speed at each waypoint is set to the minimum speed within the speed range for the assigned risk. Once again, the
path is filtered to account for deceleration and acceleration. This path is used as the starting point for determining a path that will meet the desired elapsed time.

The process by which the path is sped up is predicated on two assumptions. The first assumption is that the process of assigning path segments to risk levels has normalized risk. The second assumption is that a small linear increase in speed linearly increases risk within each level (i.e. increasing speed by 10% in safe terrain and increasing speed by 10% in slower, high risk terrain will result in the same overall risk increase). The speed ranges for each risk level are assigned to help maintain this assumption.

Given these two assumptions, the algorithm to increase speed iteratively adjusts a speed scale factor which is applied to the speed for every point in the path. The speed at each waypoint is limited to the lower of the maximum permissible speed or the upper speed bound for the assigned risk level at the point. The iteration process is either terminated by achieving the desired elapsed time or by maximizing the possible speed at all points along the route. In the latter case, the algorithm reports that the desired elapsed time was impossible to achieve.

5.3 Determining Speed on Raceday
Analysis of other competitors during the race qualifiers leading up to the event allowed the Red Team to estimate elapsed times for the other racers. Based on this estimation, the Red Team projected that other racers would not achieve elapsed times much less than 7hrs. This was determined by observing maximum speed of each vehicle at various difficulties of terrain, and factoring this by our internal estimate as to what the probability of success of that vehicle at each of those given speeds.

Given an analysis of this information, Highlander was commanded a speed profile with an elapsed time of 6hrs 20mins, to guarantee a win. Sandstorm was commanded a time of 7hrs 2mins with additional built in conservatism to guarantee a finish.
5.4 Accuracy of Pre-planned vs. Actual Elapsed Time

During testing, preplanning projected elapsed times for each robot within 14% for Sandstorm and within 2% for H1ghlander, as shown in Figure 3 and Figure 4. This was accomplished by an accurate vehicle model, conservative speeds and a good understanding of the capabilities of the robot built into the post-processing.

This is significant since it allowed the Red Team to predict with confidence the actual elapsed time for each of the robot with a relatively small margin of error. It additionally allowed us to refine our methods of preplanning over time to help decrease the disparity between actual and preplanned times.

![Figure 3: Projected vs. Actual times H1ghlander](image1)

![Figure 4: Projected vs. Actual times Sandstorm](image2)
6 Terrain Data

Speed setting and path detailing are predicated on a good understanding of the anticipated terrain. Information about where washouts can occur, and where there are known dangers such as gates and underpasses assists in detailing the route in both geometry and speed. Sources of information for terrain understanding include United States Geological Survey (USGS), private satellite imagery, and field-collected topography. Each of these data sources can be considered to have a level of confidence dependent on resolution and ground-truth accuracy. Topography generated by the team is generally superior to high resolution satellite imagery, which itself, is generally superior to publicly available flyover imagery and contour maps.

6.1 United States Geological Survey (USGS)

Coarse information of terrain is available from USGS maps which provide road and elevation information for any desired region in the United States. This data is typically of low resolution and/or poor ground truth accuracy. In the Mojave Desert, where the race was held, data from USGS typically had 15-30 meter resolution for digital elevation maps, up to 1 meter Black and White imagery, and poorly registered Digital Road Map data. Examples of both are shown in Figure 5.

![Figure 5: USGS Imagery](image-url)
6.2 *Satellite Images*

The Red Team utilized one-meter resolution color satellite imagery of the entire race area. Recent imagery was acquired in two "flybys," of areas deemed of high importance to race day. Starting chutes, jersey barriers and recently graded berms were clearly visible as seen in Figure 6. This imagery indicates washouts and other features that could impede the vehicle. On race morning, the Red Team had 100% coverage of Space Imaging Data of the region of interest.

![Figure 6: Satellite Photo of Start](image)

6.3 *Topography*

Detailed road topography data was acquired by driving along roads while collecting range measurements with a LIDAR range scanner. This data consisted of a height map reconstructed by solving for the position of each range measurement in 3-D space. The resulting height map was then evaluated for cost per vehicle constraints, resulting in a cost map similar to those generated by the robot navigation. The resulting surface models provide resolution and accuracy that are unobtainable from satellites or from traditional maps. The
quality of this data is high, but only covered 3% of the actual race route, since the team performed little reconnaissance in the race region. An example of the detail of topography is shown in Figure 7. In this figure, the high and low cost regions are identified, where the low cost region exists on the actual location of the road.

![Figure 7: Topography Data overlaid on imagery](image)

7 Verification

The verification step helps ensure that each preplanned route is free from errors prior to a robot executing it. The verification process is performed in three ways: (1) in-line as an automated method which operates periodically while the route is edited, (2) through multiple reviews by human editors, and (3) through an automated external independent check on the final route.
7.1 Automated Inline Verification

The inline verification process provides human editors periodic updates of locations where the path being edited violates any constraints. The specific constraints considered are: (1) exceeding of corridors boundaries, (2) path segments with radii tighter than a robot’s turning radius, and (3) areas where the route is very narrow and warrants extra attention. Each of these potential problems is flagged for review by a human editor. These flags are then used as focal points for interpreting the path.

7.2 Human Review

Editors review each segment multiple times to ensure the route final route is of high quality. While detailing a route, each segment undergoes an initial review by editors which fixes major problems. The first review looks for any errors in the output of the automated planner, and attempts to identify areas of high risk for a robot, such as washouts. These high risk areas are then flagged, to be confirmed in a second review. A second review takes the output of the first review, and refines the route, confirming marked “flags” and adding additional “flags” for any high risk areas missed in the first review. The expectation is that after completion of the second review there will be no need for additional editing of the geometry of the route. In the 3rd and 4th reviews the main focus is to verify that all problems identified by the automated inline verification process have been cleared, as well as to confirm that any problems identified by the automated external verification algorithm are addressed.

7.3 Automated External Verification

An automated external verification process operates on the final output to the robot and checks heading changes, turning radius, speeds, and boundary violations. In addition, the verification process outputs warnings where there are areas of high slope and sections of narrow corridors along the path. These warnings are used to identify areas for the human editors where extra care should be used. The verification process also produces a number of strategic route statistics such as a speed histogram for time and distance, a slope histogram, and a path width histogram. These statistics are used in determining the target elapsed time for the route and in estimating the risk for the route. This process is repeated several times as the path detailing progresses until the route is deemed safe for the robots to use. Figure 8 shows the detailed statistics for Sandstorm’s route in Grand Challenge 2005.
Comparison of 2004 vs. 2005 Grand Challenge

The 2005 Grand Challenge course was much simpler than the 2004 Grand Challenge course. The specific route given by the race organizers was overall straight, wide, and had very few areas of large slope change. In many regions, the most difficult sections for an autonomous vehicle were tamed with well defined berms (see Figure 9) and the grooming of washouts.
This taming of regions contrasts with the 2004 Grand Challenge where grading was not as widespread. Another way to compare the two routes is compare Figure 10 to Figure 11 statistics on the 2005 and 2004 routes. In these graphs, you can see that this year’s course had very few segments greater than 5 degrees of slope. Compare this to last year’s course. Specifically last year’s Grand Challenge had approximately 17.5 miles of slopes greater than 5 degrees; this year’s grand challenge had less than 2 miles.
Figure 10: Grand Challenge 2005 Statistics

Figure 11: Grand Challenge 2004 Statistics
As a result of grooming of washouts and the creation of berms, many areas that the Red Team identified as high risk were in fact tame. Had the Red Team known the full extent of the grooming of paths, the targeted elapsed time would have been shorter, resulting in faster targeted times for both Highlander and Sandstorm. This did not harm other teams as they did not use information in order to slow their vehicles down for hazardous areas such as washouts.

9 Performance on Race Day

On the morning of the 2005 Grand Challenge, the routes for the two robots were generated as planned, and well within the two hour limit. The speeds set were determined by the race strategy as mentioned in the Speed Setting section, and resulted in preplanned elapsed times of 6hrs 20m for Highlander, and 7hrs 2mins for Sandstorm. The output route had no unexpected/fatal errors with all remaining violations in the route being well within nominal.

As a result of this path, and the superb navigation on board, both vehicles successfully completed the Grand Challenge. Highlander finished in 7hrs 14mins, and Sandstorm finished in 7hrs 5mins. Highlander fell short of its preplanned time by approximately 55 minutes as a function of engine trouble. Sandstorm came within 3 minutes of its planned time. Though this was enough to complete the Grand Challenge, it was not enough to win the prize money as “Stanley” Stanford’s entry completed the course in 6hrs 54mins.

10 Conclusions

Preplanning was a success. Both robots completed the race within the 10-hr time constraint, with very little error. As a comparison to the other competitors, Red Team had the most extensive preplanning methodology with the strongest ability to detail exactly where the robots would travel as well as at when they would arrive at a particular area at a particular time. Both vehicles were able to successfully follow the path given to the robot and as a result smoothly entered and exited turns and curves. The speeds set by preplanning were well within the vehicle’s abilities and allowed the vehicle to achieve the commanded speeds safely without the danger of a singular event disqualifying/incapacitating the vehicle. The terrain data coverage was more than sufficient, with complete coverage of the race area in Satellite imagery.
Verification gave the team confidence that the route was truly complete, and that there would be no unexpected errors in the route along the race path.

Given the objective of finishing the race while racing against the desert, the Red Team completed its goal. Given additional information as to the extent of grooming in the route, it is possible that the team could have planned for faster target times for both vehicles, perhaps guaranteeing a win with Sandstorm, but this information was not known a priori.

Given what the team knew, the Red Team Preplanning for the Grand Challenge was a success. The technologies, tools and methods for preplanning were superb.

11 Future Work
Preplanning is currently a process that is largely done by humans with computer assistance. One primary goal is to automate some of the most time intensive or error prone aspects of this task.

Areas where Red Team Preplanning could be improved in the future are:

- Replace the spline interpolation with an automated planner
  - Automatically check, and correct curvature for turns
  - Automatically bias the vehicle away from cliff edges using digital elevation maps
  - Automatically determine driving speed for regions based on road databases/feature extraction
- Utilize road extraction technology to determine roadway widths
- Create a feature extractor to identify washouts/other hazardous obstacles automatically
- Reduce number of human editors needed
- Increase the resolution, quality, and amount of a priori data

12 References


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