Driving Autonomously Offroad up to 36 km/hr

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Abstract

An automated HMMWV has driven autonomously offroad at speeds up to 36 km/hr. Key features of the implementation that enable driving at these speeds are (1) planning the next 20 m with stable clothoid trajectories, and (2) increasing the lateral clearance to obstacles at higher speeds. The clothoid trajectories address dynamics in planning the vehicle's immediate path. The speed-biased clearance improves the safety margin for the vehicle over a range of speeds.

1 Introduction

Two of the challenges facing offroad autonomous driving systems are detecting obstacles in time to respond and driving as fast as the terrain allows. While sensing capabilities are being developed in other efforts, the focus of this work is to drive the vehicle offroad at relatively high speeds on terrain that is known to be within the capabilities of the sensors to detect obstacles in time to react to them.

Figure 1: NIST HMMWV

The NIST HMMWV[1] (Highly Mobile Multipurpose Wheeled Vehicle, Figure 1) has driven on benign terrain, where the only obstacles are easily detected by the vehicle's sensors. In the present work, the vehicle drove at 36 km/hr on rolling grass-covered meadows where the obstacles were large trees and shrubs.

A key problem is that latencies and cycle rates of sensing and control in multiple reference frames lead to instabilities. Clothoid trajectories provide a stable reliable method for planning the vehicle's path for the first few seconds of lookahead. The clothoids used are dynamically feasible trajectories that take into account the turning rate of the steering mechanism.

The second main problem is that the vehicle was brushing past trees at 36 km/hr. This issue is addressed by maintaining appropriate lateral clearance to obstacles given planned vehicle speed. Vehicle speed and lateral clearance to obstacles are considered together by the path planner as it plans both steering and speed trajectories to avoid obstacles.

The impact of this work is that the sensorimotor integration and control requirements for driving offroad at high speeds have been met in anticipation of future advances in terrain sensing and interpretation capabilities. The system will be ready to take advantage of these improvements to drive at speeds limited by the traversability of the terrain, within the limits of acceptable risk given the competence of available terrain sensing and analysis.

2 Related Work

The PRIMUS program recently demonstrated offroad autonomous driving up to 25 km/hr with a small tracked vehicle, the Wiesel 2. [6] Similar path following and obstacle avoidance capabilities were displayed. A similar, but faster (4 Hz) scanning LADAR range imager was used to detect obstacles.

Kelly [4] provides an excellent analysis of the challenges offered by high speed offroad driving and a detailed solution. The present work focuses on performing as much of the necessary analysis as possible off-line in order to minimize the computations required online.

3 Approach

The present work is part of a larger effort. The mobility system is sketched in Figure 2. The mobility software is designed in accordance with the NIST RCS Reference

1. Certain commercial products are identified in this paper to describe our study adequately. Such identification is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

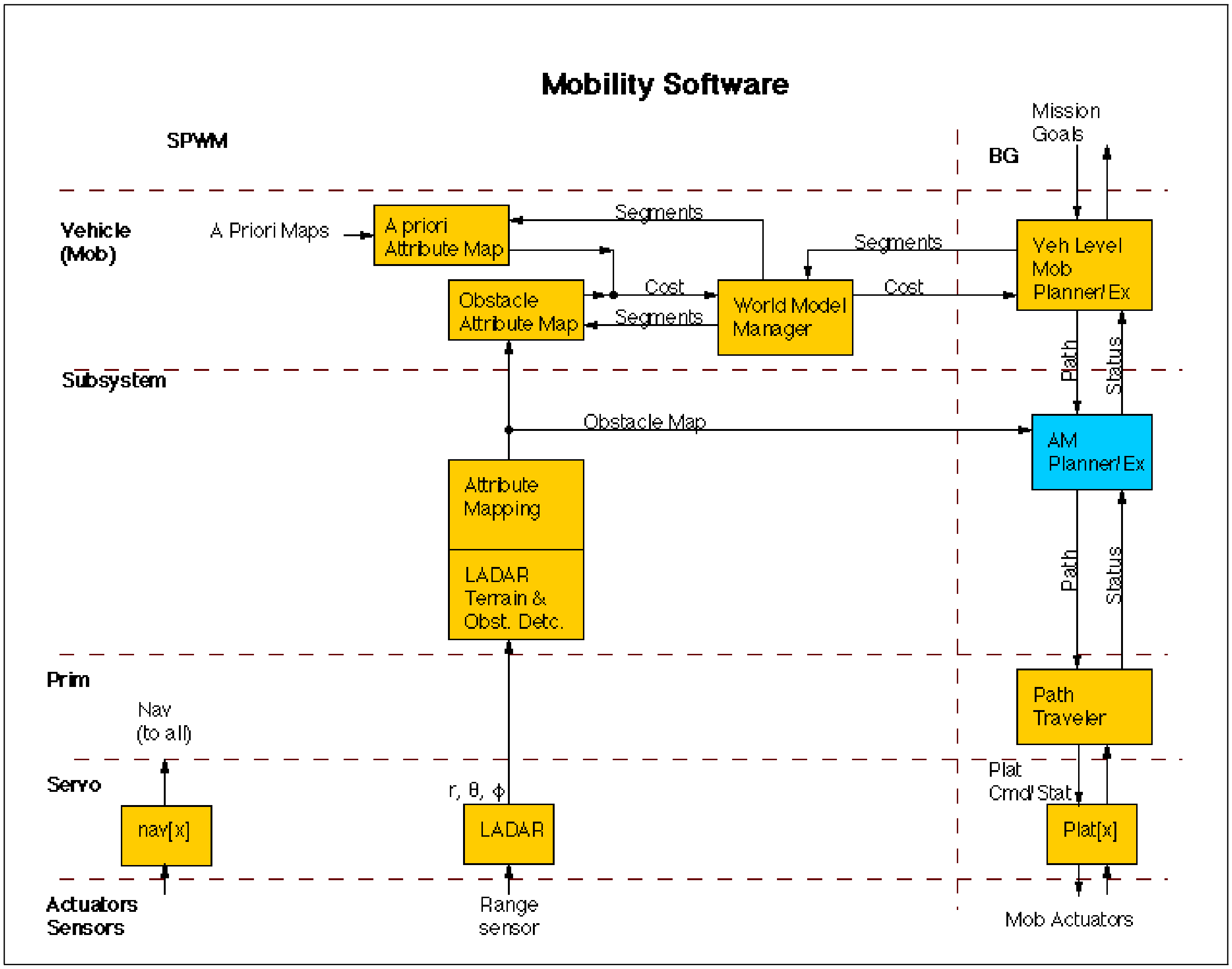

Figure 2: Mobility Software Architecture

Model Architecture. [1] [2] The focus of the present work is the AM (Autonomous Mobility) Planner/Executor. Plans at higher levels are provided from mission plans and vehicle level subsystems. Obstacles and the vehicle's position and attitude are provided by onboard sensors. These data and plans are integrated by world models. AM planning takes place in a local vehicle reference frame, and the planned path is followed by the Path Traveler.

The AM Planner is presented a path by the Vehicle Level Mobility Planner based on the best information available to it. This is augmented with the latest Subsystem level obstacle map, based on data integrated from the range camera (Figure 3 and Figure 4) and vehicle motion sensors (GPS and inertial). Obstacle detection and terrain analysis are based on data from the time-of-flight scanning LADAR range camera. [3] The range data and vehicle position and attitude are integrated in a North-oriented reference frame (Figure 5).

These data are translated into a vehicle-oriented local frame whose origin is located at the position where the vehicle is predicted to be when the path being planned will be followed (Figure 6). [5] A large set of paths the vehicle

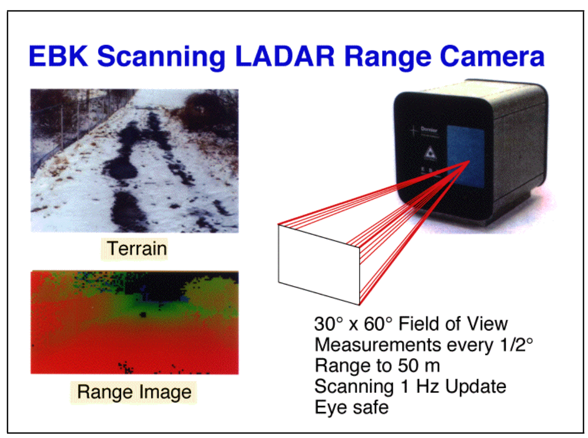

Figure 3: LADAR

is capable of following are precalculated off-line (Figure 7). Online planning consists of selecting the best obstacle-free path among these. Off-line, the trajectory-to-cell table relates each path segment to the cells through which it passes. This relation is inverted and the cell-to-trajectory table is used online to discover which path segments are blocked by obstacles (Figure 8).

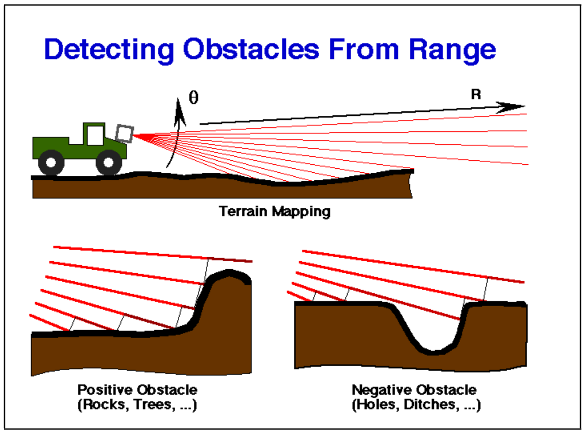

Figure 4: Detecting obstacles in range data

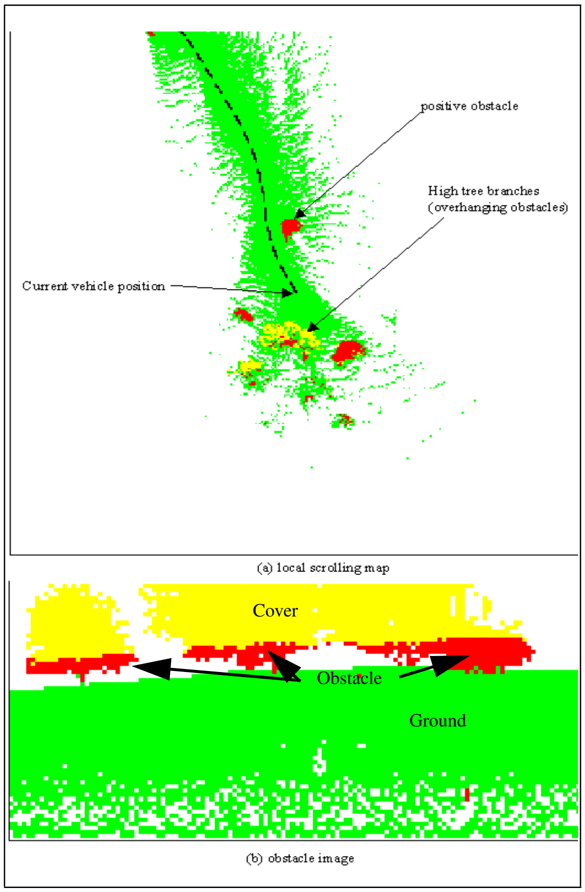

Figure 5: Obstacle map and classified LADAR image

Simple straight-line segments worked at low speeds, but were unstable at high speeds. Latencies, discretization, and translating among reference frames contributed to the problem. A key component of the solution is the use of path segments in the first few seconds that are dynamically feasible given the response characteristics of the steering mechanism. Clothoidal path segments of 20 m length were generated for a range of initial steering angles by simulating steering command sequences for a range of vehicle speeds (Figure 9).

A set of 20 m long clothoids is used to cover a range of initial vehicle velocities and turning rates. An example is show in Figure 10. The set of segments feasible for 10 m/s travel is assumed to be traversable at lower speeds as well. A large space of trajectories can be considered in online path selection with this method. Beyond 20 m, segments to 50 m are treated with straight line approximations because the AM path will be replanned before those segments are traversed.

3.1 Speed-biased clearance

Two problems remained, and speed-biased clearance copes with both. First, the vehicle drove too close to obstacles at high speeds. The vehicle would brush its mirrors and antenna mounts against tree branches when it was driving fast as well as slow. Not only did this behavior risk damaging equipment on the vehicle, but also it left little room for error.

The second problem was that the path would sometimes become blocked while the vehicle was driving closely around an obstacle near the path. This could occur because new data showed the obstacle to be larger than previously sensed. Another source of this problem was that the vehicle-oriented map could move with the vehicle such that the obstacle had expanded into a previously clear cell. This blocked the vehicle's available paths when the vehicle was near the obstacle. When the vehicle was far enough from the obstacle, a sharper curve could be used at lower speed to take the vehicle away from the obstacle. However, when the vehicle was already at its lowest speed, no other recourse was available.

These problems were addressed by increasing clearance requirements with increases in speed. Lateral clearance of each path segment is related to the segment's speed. In general, 0.8 m of clearance (the width of two 0.4 m cells) was added to each clothoidal segment for each step increase in speed above the minimum. The straight-line segments from 20 to 50 m are all considered to be up to 10 m/s, so they have the same width as the 10 m/s clothoids. The concept is illustrated by the cartoon in Figure 11.

This policy is implemented by using increasing widths of path segments in building the trajectory-to-cell and cell-to-trajectory tables. The wider paths cover more cells in the trajectory-to-cell table, and when the mapping is inverted, more cells affect the path in the cell-to-trajectory table. This increases the clearance between the vehicle and obstacles at higher vehicle speeds, and it provides additional buffer so the vehicle can resort to slower paths in case faster paths become blocked as the vehicle approaches.

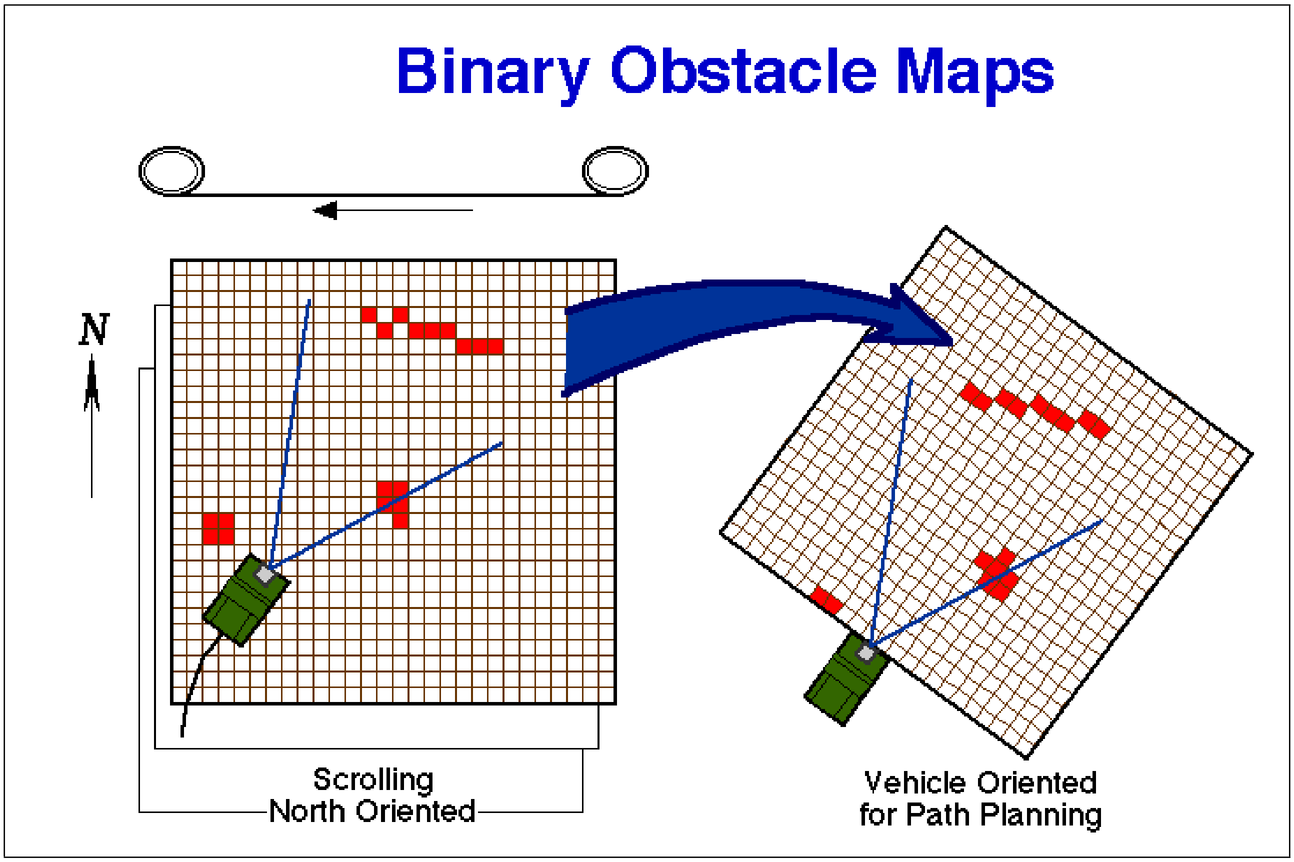

Figure 6: Coordinate frames

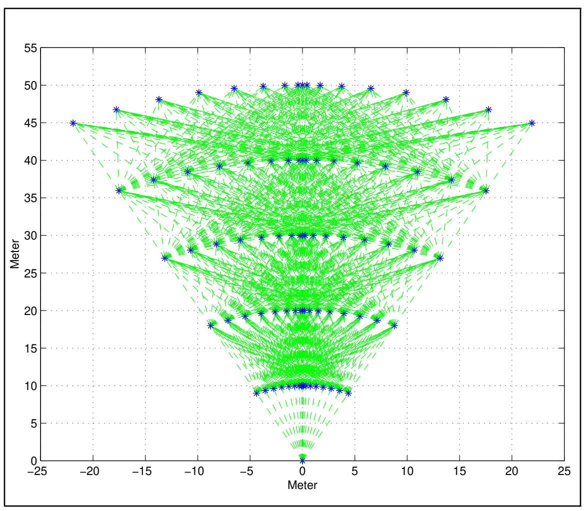

Figure 7: Ego-graph of vehicle-oriented paths

4 Conclusion

These techniques enabled the vehicle to travel over rolling meadows at speeds up to 36 km/hr (10 m/s) while avoiding obstacles that were well within the vehicle's current sensing capabilities, such as large trees and shrubs.

In general, it is probably desirable for the vehicle to negotiate the terrain rather than avoid obstacles. This emphasizes the notion that terrain is traversable at some speed depending on its particular characteristics. This will require a more sophisticated terrain analysis and planning model than the binary model used presently. However, the more complex model should enable the system to address another challenge looming on the horizon. For many applications, it is necessary to maneuver the vehicle in tight quarters, in some cases even to the point of driving through overhanging branches and pressing through brush. It is hoped that a general solution could address the entire spectrum from high speed driving over a variety of terrain to maneuvering in tight quarters.

Acknowledgments

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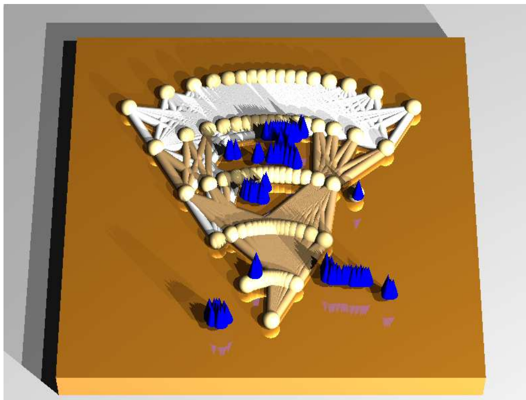
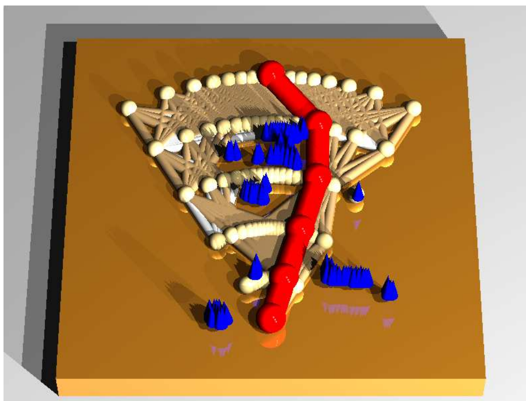


(a) obstacles blocking paths, via cell-to-trajectory table



(b) least costly path found by searching the graph

Figure 8: Local path planning

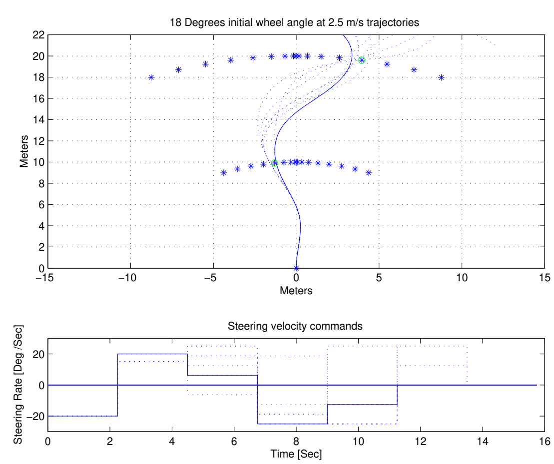


Figure 9: Steering segments

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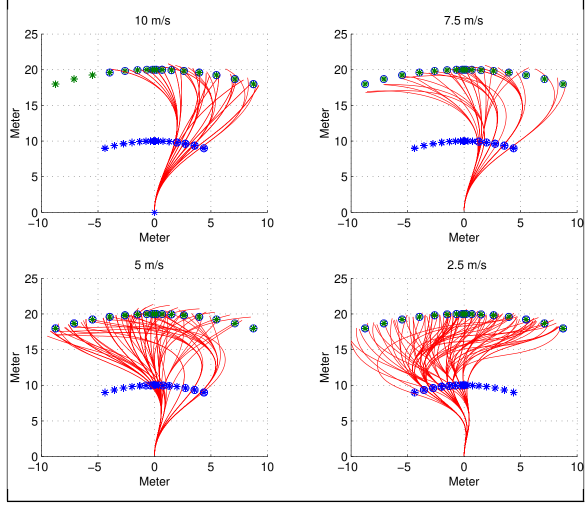

Figure 10: A set of steering segments

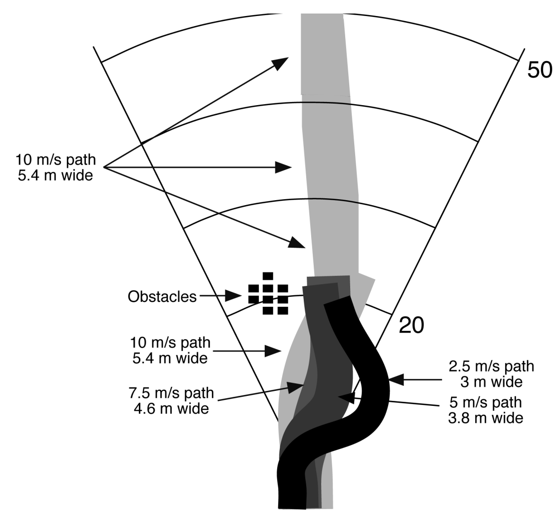

Figure 11: Speed-biased path clearance

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