MULTI-BODY VEHICLE DYNAMICS SIMULATION BASED ON MEASURED 3D TERRAIN DATA

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ABSTRACT

Due to its influence on suspension deflection, vehicle rollover, and tire normal forces, terrain modeling is an important factor when performing vehicle dynamics simulations. There has been significant research on 2D (longitudinal) road profile modeling for purposes of measuring ride quality, road roughness and condition, and evaluating suspension design. But there has been little study of 3D road geometry modeling, which may be useful for vehicle rollover and banked-road handling analysis. This study focuses on 3D terrain modeling for the purpose of vehicle dynamics simulation. Terrain data was collected using a LIDAR sensor mounted on an instrumented vehicle. This data was used to generate a 3D road representation that was imported into a multi-body CarSim vehicle simulation. A challenge with the full 3D representation was to determine the level of signal filtering necessary to smooth the raw LIDAR point cloud for an appropriate road representation. To find the optimal filtering, an iterative process was used that minimizes RMS error in roll and pitch by comparing in-vehicle measurements to simulated vehicle responses. At a particular spatial filtering frequency, a good match was obtained between simulations and measured vehicle responses. The contribution of terrain to vehicle roll dynamics was also studied by comparing simulated traversal of roads with and without vertical terrain features.

Keywords: 3D road modeling, terrain dynamics, LIDAR, road measurement, CarSim

1. INTRODUCTION

Terrain modeling plays an important role in road characterization and vehicle dynamics simulations. Not only do road roughness measurements indicate road health and ride quality, but the profile of the road can be used as an input to a vehicle dynamics model to find the chassis response. Over the years, different road profile measuring devices like the GM profilometer and Longitudinal Profile Analyzer (LPA) have been developed to measure two-dimensional road/terrain profile. The GM profilometer obtains vertical motion by integrating the vertical acceleration recorded by an accelerometer (Spangler et al., 1996). On the other hand, LPA uses an angular displacement transducer to measure angular travel of a horizontal beam whose one end is attached to a trailer wheel using. Some recent studies (Imine et al., 2005; Imine et al., 2006) combine LPA measurements with observer design methods to estimate two-dimensional road profiles. Also, there has been significant research on statistical modeling of two-dimensional terrain profiles under each tire (Chemistruck et al, 2009). This data is also useful for correlating vehicle motion with particular roads and road location (Dean et al., 2008).

This study focuses on 3D terrain modeling for vehicle dynamics simulations. Most terrain measurement studies focus on road characterization using 2D longitudinal road profile under the tire. However, 3D digital terrain information is necessary for vehicle dynamics simulations involving lateral motion. With the increasing use of mobile Light Detection and Ranging (LIDAR) systems, it is possible to record 3D maps of the road. Although terrain mapping with the aid of LIDAR is very common in robotics, LIDAR mapping is hardly used for the purpose generating real terrain data for vehicle dynamics simulations. One of the recent studies by Detweiler, 2009, used a laser scan for digital terrain modeling. They compared the chassis response from a 7th order vehicle ride model on a real terrain with the measured responses and obtained a good agreement. Studies by Imine et al. [5, 6, and 7] used a similar ride model. However, such studies are focused on the vertical forces acting on sprung and unsprung masses rather than cornering forces acting on a vehicle at the tire-pavement interface when a vehicle is moving on a curve.

Although 3D geometry of a road is often used in vehicle simulations for analyzing highway design and safety (Stine et al., 2010), most of such work has focused on idealized roads rather than measurements from actual roads. For most vehicle stability studies, terrain profile is often ignored even though it is well known that terrain dynamics contribute to the resulting roll dynamics of the vehicle. The challenge in using 3D profiles for roll analysis of a vehicle is the presence of bias and noise in the 3D LIDAR measurements. This is similar to errors seen in 2D profilometer studies where advanced filtering techniques are used to remove similar measurement artifacts. But unlike these established 2D methods, the filtering techniques for 3D smoothing of road measurements are not yet well established. This study therefore considers the optimal smoothing of 3D terrain profile data for vehicle simulation studies.

The rest of the document is organized as follows. Section 2 explains the methodology used for field terrain measurement and subsequent vehicle dynamics simulation on 3D terrain. The results obtained from the simulations on the data considered for this study are discussed in Section 3. This paper concludes with a discussion of conclusions from this work in Section 4.

2. METHODOLOGY

As shown in Figure 1, the steps involved in the methodology of this study can be summarized as follows:

1) First, collect terrain profile data using an instrumented vehicle,
2) Next, perform CarSim simulations on a filtered and gridded representation of the roadway. Compare the measured and simulated roll/pitch, and finally
3) Iteratively change the smoothing filter that transforms raw data to the gridded representation in order to find the spatial frequencies that best minimize RMS error.

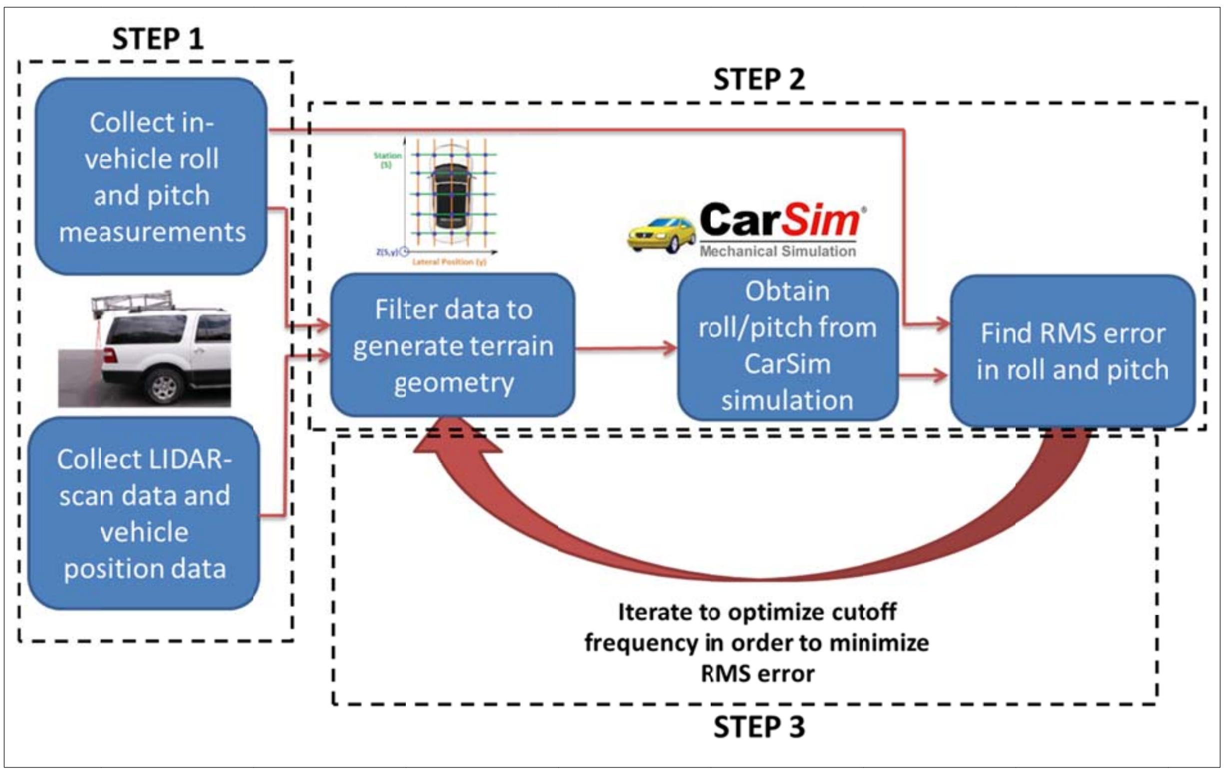

Figure 1: Summary of methodology

2.1 Terrain Data Collection Using Instrumented Vehicle

A vehicle equipped with LIDAR, a Global Positioning System (GPS), and an Inertial Measurement Unit (IMU) was used for terrain mapping as shown in Figure 2. Each LIDAR scan includes 361 data points subtending an angle of 180 degrees at 0.5 degree increments. One complete lateral scan occurs every 0.8 meters when traveling at highway speeds (30 m/s). While

LIDAR scans the road in the lateral direction, the GPS-IMU unit gives global position and orientation of the vehicle. Using data from all the sensors, raw terrain geometry was obtained using a coordinate transformation (Vemulapalli et al, 2009). The data presented in this study was collected while driving on Highway 322 in Pennsylvania.

Figure 2: Instrumented Vehicle for Data Collection (Vemulapalli and Brennan, 2009)

2.2 CarSim Simulation and Roll/Pitch Comparison

The 3D terrain geometry obtained by filtering raw data from Step 1 was used to simulate a vehicle maneuver in CarSim. CarSim is a multi-body simulation software package widely used in the automotive industry that predicts vehicle performance. System-level behavior is predicted with high fidelity using a high-order mathematical model that solves the nonlinear ordinary differential equations associated with the multi-body physics of a vehicle. These physics include models or approximations of the primary chassis subsystems such as tires, suspension, engine, etc. CarSim was chosen over other packages because it allows the user to define and/or import 3D terrain geometry for performing complex simulation tasks. For the simulation runs, the simulated vehicle was driven along the same vehicle trajectory as the instrumented vehicle at highway speed. Using the raw LIDAR data to populate a simulated road grid, the roll and pitch obtained from the CarSim simulation was compared with the measured roll and pitch from the actual mapping vehicle, as shown in Figure 3. In this case, the pitch obtained from CarSim simulation does not match the measured response very well. The noise from the sensors results in a noisy road profile and causes a disagreement between simulation and experimental data.

2.3 Iterative Filtering to Minimize RMS Error

As mentioned earlier, a high value of RMS error was obtained due to noisy measurements. In order to reduce this noise, a second-order Butterworth low-pass filter was used and 3D terrain geometry was generated. However, if one is too aggressive in smoothing the noisy field measurements (by using an inappropriately low value of the cutoff frequency of the smoothing filter), there is a pronounced loss of terrain information as shown in Figure 4. For this reason, simulations were performed for a wide range of cutoff frequencies in order to determine the optimal frequency that corresponds to minimum RMS error in roll as well as pitch.

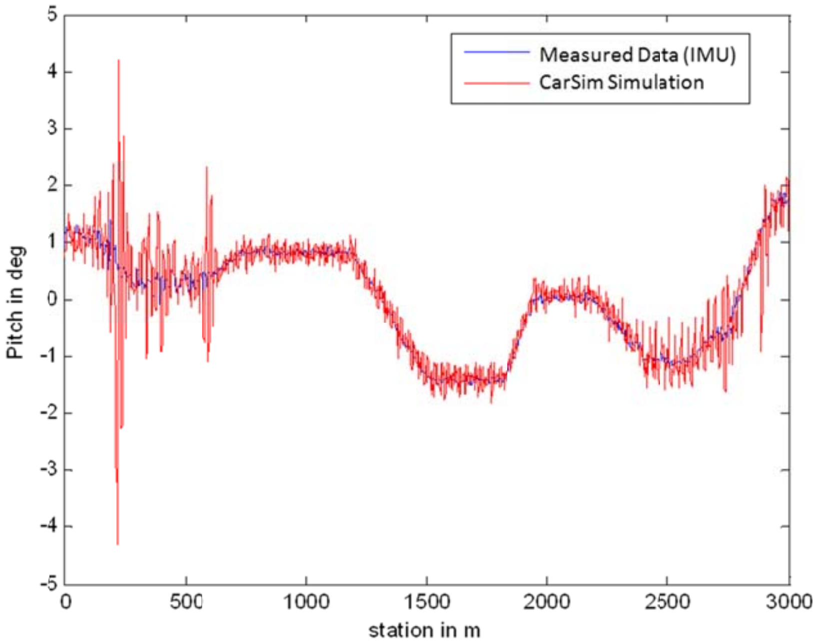

Figure 3: Comparison of pitch between CarSim simulation and measured data

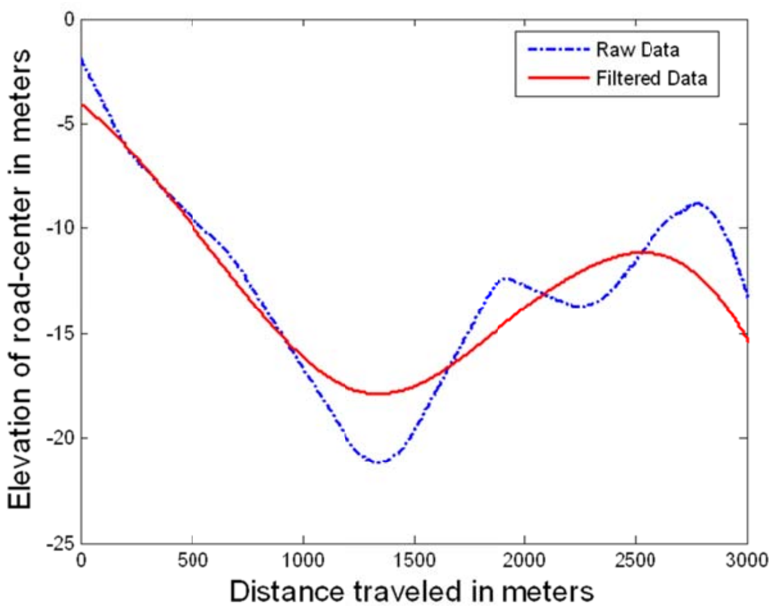

Figure 4: Road-center elevation profile after applying a low-pass filter with a low cutoff frequency

3. RESULTS

3.1 Optimal Filtering

It was observed that a minimum value of RMS error in roll and pitch was obtained at approximately the same levels of spatial smoothing (e.g. the same normalized cutoff frequency) in both the longitudinal and lateral directions. This optimal frequency corresponds to one cycle per 27 meters of distance traveled as seen in Figure 5. Although not presented in this paper, the same procedure was performed on four other road-datasets and approximately the same cutoff frequency was obtained in all the cases. As shown in Figure 6 and Figure 7, the roll and pitch values from CarSim simulations agree very well with the measured roll/pitch data for this optimally filtered terrain data. RMS errors for the roll and the pitch were 0.19 and 0.18 degrees, respectively.

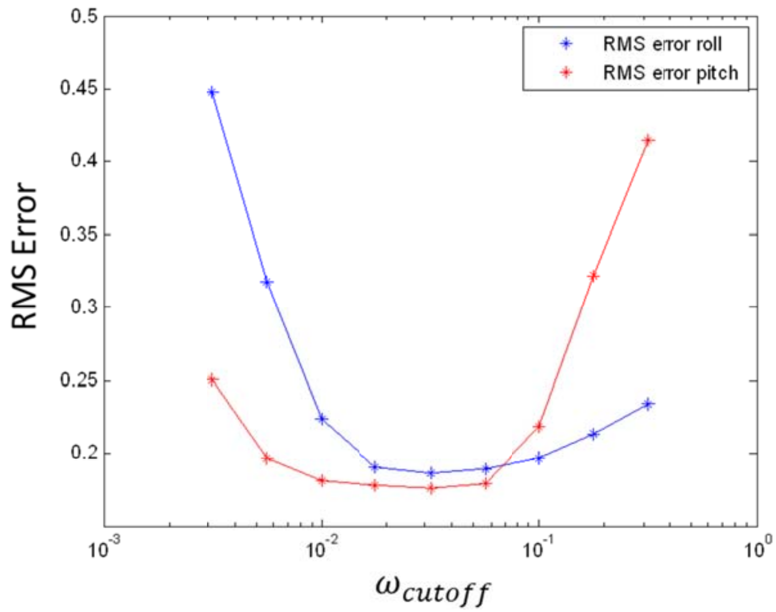

Figure 5: RMS roll/pitch error vs. normalized cutoff frequency

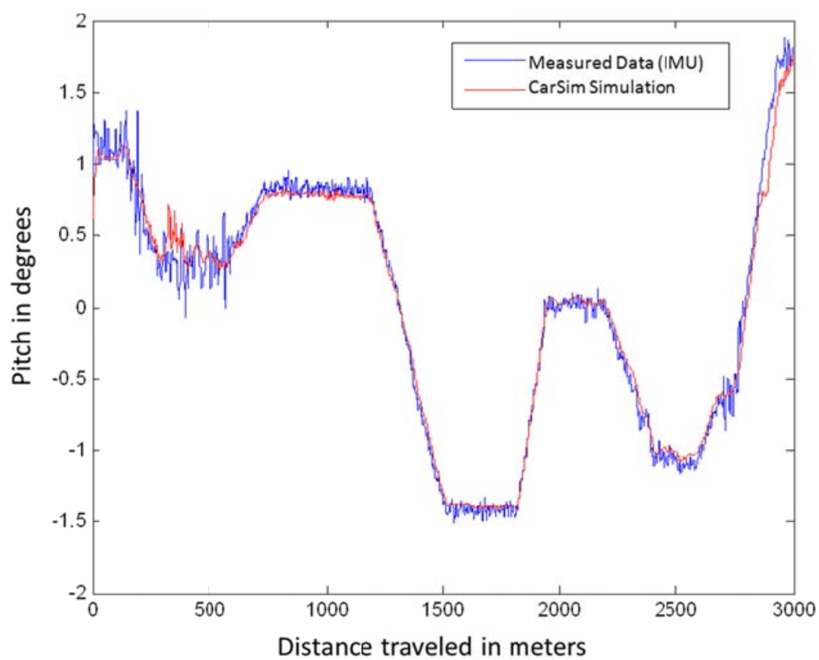

Figure 6: Pitch comparison for minimum RMS error case

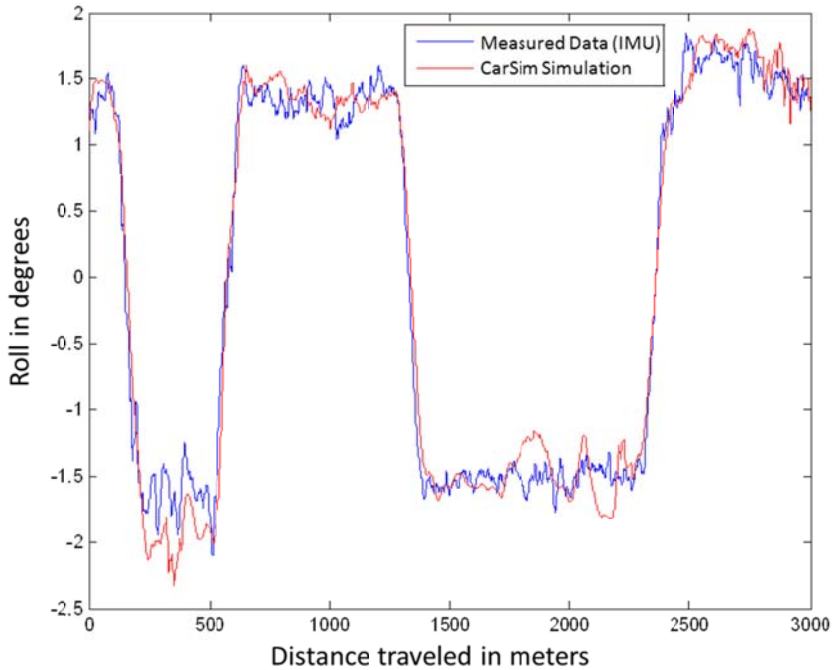

Figure 7: Roll comparison for minimum RMS error case

3.2 Terrain Contribution to Vehicle Roll Dynamics

During normal driving situations, the driver's steering inputs are very small. In fact, they typically provide so little excitation of the vehicle's roll dynamics that the road superelevation contribution from the terrain can dominate the in-vehicle roll measurements. However, for aggressive vehicle maneuvers, the steering dynamics can have a significant contribution and hence the resulting roll response will be the superposition of road-induced roll and maneuver-induced roll. It is thus important to discern the relative contribution of terrain versus steering inputs as many anti-rollover stability systems must isolate the driver-induced maneuvering effects. Further, knowledge of road-induced roll effects may significantly increase the signal-to-noise ratio of steering-induced roll versus terrain influences.

To quantify the relative contribution of terrain versus steering during normal driving situations, the vehicle simulations described previously were again used. However, the road profile was modified to be a perfectly planar road with the same (XY) vehicle trajectory as recorded from the in-field measurements. In this setup, the driver model is producing steering inputs that follow the XY-plane trajectory, and thus the roll dynamics produced in simulation are only those induced by such normal steering events. By comparing this simulated roll angle to the angles measured on an actual vehicle, the contribution of non-planar road geometry can be studied. The results are shown in Figure 8 where it is clear that the non-planar (roll) road profile is an important factor in predicting overall vehicle response in roll.

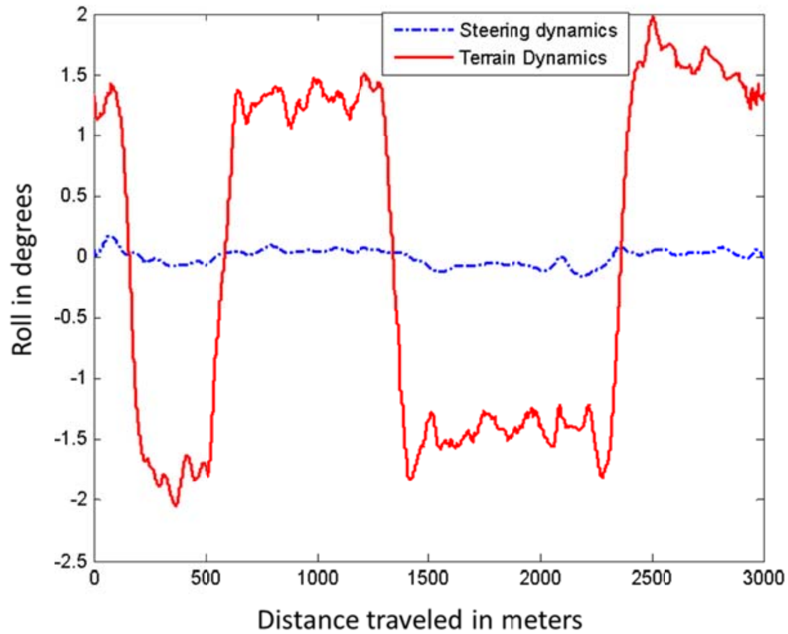

Figure 8: Steering dynamics and terrain dynamics contribution to roll dynamics

4. CONCLUSIONS

In this paper, a methodology for optimal 3D terrain modeling was presented. The results from this research indicate that multi-body simulations of a vehicle moving over digitized terrain profiles can predict vehicle response quite well. The results also indicate that a specific spatial frequency of 1 cycle per 27 meters apparently captures most of the terrain influences on roll/pitch of a typical highway. The results suggest that, if chassis motion in pitch and roll is of primary concern, it may be possible to represent terrain geometry by considering LIDAR scans that are sparse relative to the vehicle size. This is in contrast to typical road scans which are used to study suspension displacement due to potholes, bumps, etc where one would clearly need a higher cutoff frequency for appropriate fidelity.

The contribution of terrain to the roll dynamics was also analyzed. Terrain information was found to play an important role in predicting overall vehicle response using simulations. This capability to isolate terrain effects from driver inputs can lead to improvements in vehicle stability algorithms, better multi-body simulations studying the impact of terrain geometry on vehicle safety, and even improvements in vehicle localization research (Dean et al., 2008).

As future work, the results suggest that it should even be possible to simulate roll motion caused by driving behaviors where there is significant motion across multiple lanes. In this study, the LIDAR sensor used to scan the terrain gives enough data points to allow the representation of multiple lanes. This is unlike many profilometers today that record terrain information only under each tire. One could verify this easily with field experiments including aggressive lane changes on typical roads. Additionally, there should be verification on additional vehicles and LIDAR sensors that the optimal cut-off frequency does not significantly change across changes in either platform.

Another area of future interest is the use of digitized roadways for use in vehicle driving simulators with motion systems. Many driving simulators are used in automotive industries as well as universities to analyze new vehicle or roadway designs, to evaluate the user experience, for driver training, and for vehicle dynamics research studies such as rollover stability systems. The digital 3D terrain modeling approach in this paper can be used for designing realistic road geometries for such vehicle simulators to produce simulated vehicle motions that optimally match on-road behavior.

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