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Techniques for averting and correcting errors in 3D terrain topology measurements

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Abstract

The emergence of high-fidelity vehicle and tyre models has raised the requirements for 3D terrain measurement capabilities. Inaccuracies that were once tolerable for measurement of general terrain roughness are no longer acceptable for these new applications. The data inaccuracies that arise from small inertial errors are compounded by difficulties in managing massive file sizes. These faults are most apparent when combining multiple lanes of data in the post-processing phase. This work develops two correction techniques: a general method for any terrain type and a more computationally efficient method for smooth terrain. The general terrain correction method uses overlapping points in the horizontal plane to build a discontinuity vector and applies that vector to correct adjacent lanes. While this method effectively eliminates lane-to-lane discontinuities, it is computationally inefficient for terrain that lacks localized disturbances. For simulations using smooth terrain surfaces, such as racetracks or highways, data can be down-sampled through a mean interpolation method to smooth the artefacts of inertial errors. This work provides the vehicle test engineer with guidelines to minimize inertial errors during the data collection phase as well as a post-processing tool to combine multiple lanes of high-fidelity 3D terrain surfaces.

Keywords: Terrain; Measurement; Spatial interpolation; Discontinuity

1. Introduction

Terrain measurement systems began as simple two-dimensional (2D) devices used by transportation departments and vehicle manufacturers to measure road roughness [1–5]. As computer power increased and signal processing techniques evolved, 3D terrain measurement systems were developed [6,7]. Typically, terrain measurement systems incorporate a scanning laser [8] that is rigidly mounted to the body of a host vehicle [6,7,9]. This vehicle traverses the terrain while simultaneously acquiring terrain measurements. When the vehicle encounters a disturbance, the laser translates and rotates with the body of the host vehicle. To obtain accurate terrain measurements, the motion of the vehicle must be accurately measured so that it can be removed from the laser measurement. Modern systems use an Inertial Navigation System (INS) to measure the vehicle movement [10]. The accuracy of the INS depends on the alignment of the Inertial Measurement Unit (IMU) to the laser and satellite coverage of the Global Positioning System (GPS). Typically, an INS is capable of establishing a geodetic position with 2 cm accuracy; however, a misalignment of 2 cm will adversely affect simulation data when multiple lanes of data need to be combined.

Current terrain measurement systems acquire approximately one million data points per second. This data acquisition rate improves the available signal bandwidth and allows sharp disturbances to be detected in both the transverse and longitudinal directions. Capturing these disturbances is critical; the driver's perception of ride quality is

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largely dictated by these events [11] and chassis durability is highly sensitive to transient loading. For longer stretches of terrain, storing and manipulating these data is a daunting task. One benefit of the techniques developed in this work is a reduction in the data required to represent the measured terrain topology. This representation issue must also be considered in terms of tyre interaction with the terrain. Specifically, accurate vehicle simulation requires consideration of tyre bridging and envelopment, in which the vehicle responses will not be affected by narrow dips and small stones in the terrain surface [2].

The objective of this work is to develop a method for reducing lane misalignment due to run-to-run variation in measured terrain height. The remainder of this work is developed as follows. First, a brief overview is presented on the evolution and practical applications of 3D terrain surfaces and eliminating the host vehicle's body motion from the laser measurements. Next, the method for combining multiple lanes of data is developed. Additionally, techniques are presented for effectively handling the large file sizes generated by 3D terrain measurement systems. Pavement health monitoring is discussed in the context of INS inaccuracies, followed by concluding remarks.

2. Background

Terrain measurement systems have evolved considerably from the early vehicle-response systems [12–14] to vehicle-independent measurement systems [6,7,15]. These vehicle-independent measurement systems rely on some combination of an INS, accelerometers, a distance measurement instrument, and inclinometers to remove the host vehicle's body motion from the laser data. Small misalignment between the scanning laser and the IMU will compound the error that can be anticipated from any Differential GPS (DGPS) [16]. This work exclusively considers the topology of the terrain; however, a similar host vehicle equipped with supplementary instrumentation could be utilized for sinkage [17] and other terramechanics studies [18].

The Vehicle Terrain Measurement System (VTMS) [6,7], as seen connected to the host vehicle in Fig. 1, constructed by the Vehicle Terrain Performance Laboratory (VTPL), was used to acquire the data for this work. The scanning laser, affixed at the rear of the vehicle, acquires 941 data samples transversely across a 4.2 m wide path each millisecond. The INS solution is used to estimate the laser's position and orientation in a device-centred coordinate system. Traditional inertial measurement systems only rely on accelerometer data to remove unwanted body motion from post-processed data files. The reliability of a system solely using accelerometers to remove body motion suffers when vehicle speed falls below 5 m/s [19] and in other low frequency environments. To remedy this poor reliability, the VTMS exclusively uses the INS data to mitigate low frequency motion; three coplanar accelerometers augment the INS solution for mitigating high frequency motion. This arrangement bolsters the INS solution with additional high frequency information and does not suffer from the low frequency issues common to traditional accelerometer-based systems.

The laser measures the relative distance between itself and the terrain surface (both vertical and transverse distance) in device-centred coordinates; it does not collect data concerning its absolute location in space. The accelerometers and the INS also have corresponding device-centred coordinate systems that are translated to the laser coordinate system. Once the data from each device are translated to the common coordinate system and synchronized in time, the host-vehicle body motion information is removed from the laser data. Finally, a space 3/123 coordinate transformation translates the resulting terrain data in the device-centred coordinate system to a global coordinate system, whose horizontal axes originate at the base station antenna of the INS. The global coordinates are defined such that the coordinates in the horizontal plane have their positive sense in the Easting and Northing directions, and the ellipsoidal height defines the vertical coordinate. The result of this data acquisition and signal processing is illustrated in Fig. 2. The left image is a digital photograph of a

Fig. 1. Host vehicle with attached Vehicle Terrain Measurement System.

Fig. 2. Terrain image and corresponding terrain rendering.