

A Physics-Based Vehicle/Terrain Interaction Model for Soft Soil Off-Road Vehicle Simulations

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ABSTRACT

In the context of off-road vehicle simulations, deformable terrain models mostly fall into three categories: simple visualization of the deformed terrain only, use of empirical relationships for the deformation, or finite/discrete element approaches for the terrain. A real-time vehicle dynamics simulation with a physics-based tire model (brush, ring or beam-based models) requires a terrain model that accurately reflects the deformation and response of the soil to all possible inputs of the tire in order to correctly simulate the response of the vehicle. The real-time requirement makes complex finite/discrete element approaches unfeasible, and the use of a ring or beam-based tire model excludes purely empirical terrain models.

We present the development of a three-dimensional vehicle/terrain interaction model which is comprised of a tire and deformable terrain model to be used with a real-time vehicle dynamics simulator. The governing equations of both models are physics-based, rather than utilizing popular terramechanics models that are empirical. The tire draws on a lumped-mass model based on a radial spring-damper-mass distribution. The terrain model utilizes Boussinesq and Cerruti soil mechanics equations to determine the pressure distribution and deformation of a volume of soil as a function of vertical and lateral forces applied at the soil surface by the tire. The model treats a column of soil as a system of discretized soil volumes, and the deformation of each is modeled using visco-elasto-plastic compressibility relationships that relate subsoil pressures to a change in bulk density of the soil, which in turn produces soil displacements. Different loading combinations applied by a tire passing over a column of soil will be reflected in the state of each volume of soil contained in the column, rather than treating the column of soil as homogeneous in the vertical direction and only associating one set of parameters with the entire column, e.g. a Bekker type model. Furthermore, the time-dependent elastic and plastic response of the soil to repetitive compression/rebound tire loads is also taken into account. Lateral forces produced by slip and bulldozing effects will also be incorporated into the model. These physics-based models will be integrated into a real-time vehicle dynamics simulator and is anticipated to lead to a realistic vehicle dynamic response when driving on off-road, deformable terrain conditions, especially when repeated loading occurs or non-homogeneous soil conditions are present. Additionally, the changes in soil states can be used to directly compute the energy and power required to deform the terrain. In order to retain the ability to run real-time simulations, a parallel computing approach is considered to leverage the inherently parallel nature of performing multiple independent terrain geometry queries and soil-mechanics calculations. Numerical experiments are run on a single soil volume node under a known load and for a simplified tire model applying normal forces on the surface of the terrain. Results are given for the vertical plastic soil deformation, and for the power and energy required to perform the deformation.

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INTRODUCTION

We present the development of a vehicle/terrain interaction model to be used with an existing real-time driving simulator at the US Army's Tank Automotive Research, Development and Engineering Center (TARDEC). The model will make use of existing simulation tools and terrain profile measurement information as additional requirements to the development. The US Army TARDEC ride-simulator [1] is comprised of a multibody dynamics vehicle model that is interfaced with an empirically-based deformable terrain model. The terrain model is able to query lateral and longitudinal location points on a terrain database which returns various terrain information about a data point, notably the undisturbed terrain height, the change in height, the Rating Cone-Index (RCI), and the type of terrain, e.g. soil classification code. Geometry associated with the terrain profile is a combination of low-fidelity terrain height measurements with superimposed NURBS for high-frequency content [2], and an example terrain profile is shown in Figure 1. This information is used with empirical relations developed at the Engineering, Research and Development Center (ERDC) to estimate the terrain sinkage and vehicle tractive forces under a given tire loading condition. The interaction forces at the tire/terrain interface, which are responsible for soil deformation, are then resolved as tire-spindle forces and are passed back to the vehicle model. This approach, based on empirical terramechanics relations makes several assumptions such as, for instance, the premise of equally distributed pressure under the tire footprint. The tire is assumed to be rigid, and furthermore, the soil mechanics are based on static whole wheel tests approximated as a function of vehicle speed, which leads to inaccurate results for a slow moving or rapidly accelerating/decelerating vehicle.

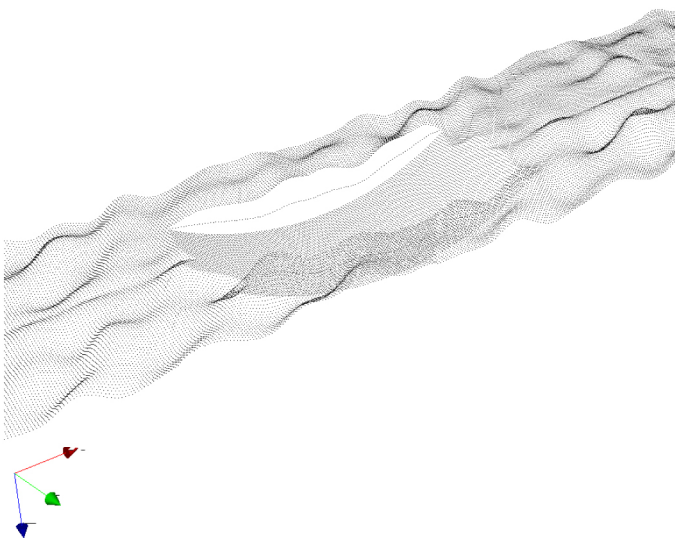


Figure 1. Terrain geometry as a heightmap, after an applied displacement

The principle behind the new Vehicle/Terrain Interaction Model (VTIM) is that the governing equations of the model are physics-based, instead of the current empirical model. The inputs to the model consist of vehicle parameters and operating conditions. The outputs include terrain deformation, vehicle power/energy requirements and tire forces. The new VTIM builds around three components: (i) a surface loading mechanism due to a non-rigid tire, (ii) a rigorous vertical soil stress/strain integration, and (iii) lateral force characterization due to soil surface shear (slip) and bulldozing forces. They rely on physics-based tire and terrain models and will be integrated into the existing vehicle model and terrain database system.

The soil mechanics equations developed result in smooth, continuous functions over the affected volume of soil for both vertical and horizontal soil deformation; however, the database will discretize these values into a three dimensional grid under the affected area for database storage purposes and to maintain the ability to run real-time simulations. The dimension and number of elements in this grid will be tailored to retain the accuracy of the original, continuous functions. Multiple forces will be applied on the terrain surface, depending on the number of tire nodes in contact with the terrain. The total pressure on each soil node is determined by superimposing the contribution from each tire force that causes subsoil stress on the particular soil node. Vertical deformation and the state of each soil node are calculated and used to update the terrain database for the next time step. They are subsequently used in an energy/power analysis that gauges the mobility and the associated power requirements of the vehicle.

In the proposed approach real-time simulations will be possible due to the inherent parallel nature of the tire node terrain queries, which will utilize parallel CPU and GPU hardware to accelerate the computation of the soil mechanics values.

VEHICLE TERRAIN INTERACTION MODEL COMPONENTS

This section contains the physics-based models that will replace the existing empirical components used in the real-time off-road vehicle dynamics simulator at US Army TARDEC. No changes are made to the vehicle model, which is a multibody dynamics-based model. The tire model is briefly presented, followed by the soil mechanics model, which is broken down into its constitutive parts with an in-depth discussion of each component.

TIRE MODEL DESCRIPTION

In order to enable real-time simulation, the tire and soil models are solved in a staggered fashion. The spring-damper tire model combines a series of lumped masses, linked to each other and the wheel rim using discrete spring-damper elements. The model consists of two components, which were detailed for hard surfaces in [3]. The first component is the

model shown in Figure 2, which incorporates both radial springs and dampers, and interradsial springs. The second component is the tire tread discretized into a number of lumped masses. Lumped masses are connected to each other and to the wheel rim using tangential and lateral spring elements. The numerical results presented in this work do not contain tire dynamics, thus the lumped mass tire tread description is excluded, but can be found in the literature.

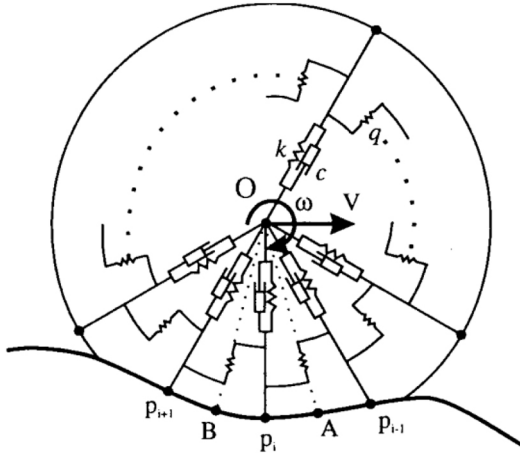


Figure 2. Radial-interradial spring-damper tire model

Each of the spring-damper elements composing the rolling radial-interradial model can either be an active element, in contact with the ground and queried using the terrain geometry database, or a passive element. In order to determine the active elements, the terrain geometry is queried for each lumped mass coordinate tuple, $r_i = \{x_i \ y_i \ z_i\}^T$. If there is penetration of the terrain geometry, then the length of the spring-damper element is calculated as

$$\ell_i = \sqrt{(r'_i - r_c)^T (r'_i - r_c)} \quad (1)$$

where r'_i is the coordinate of P_i , the i^{th} terrain contact point, and r_c is the coordinate of the center of the wheel, both expressed in global coordinates. For each active element, a Boolean activity array will be set to true (1), while for each passive element, the activity array will be set to false (0). Based on wheel rotational speed, the array will be used to minimize the number of terrain queries at each timestep. The radial force acting on the i^{th} mass element can then be expressed as

$$F_i = k(R - \ell_i) + q(\ell_{i+1} - \ell_i) + q(\ell_{i-1} - \ell_i) - c\dot{\ell}_i \quad (2)$$

where k and q are the stiffness of the radial and interradsial springs, c is the radial damping, and R is the undeformed radius of the tire. For the undeformed elements, the force F_i is zero.

SOIL MECHANICS MODELS

The physics-based soil mechanics model, developed by Ayers and Bozdech, is a combination of many different models and is the most substantial theory contribution to the project. As such, this section is broken into its constitutive parts, which include: vertical stress and sinkage, repeated loading effects, shear stress/shear displacement effects. Power and energy calculations for both vertical and horizontal soil deformations are also included.

Vertical Visco-Elasto-Plastic Model

As the soil surface contact area and the vehicle normal surface loads are known, the subsurface stress distribution needs to be determined. The method for calculating the stress in a semi-infinite, homogeneous, isotropic, elastic medium subject to a vertical point load applied on the surface was first developed by Boussinesq [4]

$$\sigma_z = \frac{3}{2\pi} \frac{1}{[1 + (r/z)^2]^{5/2}} \frac{W}{z^2} \quad (3)$$

where σ_z is the stress at the depth z , W is the point load, and r is the horizontal distance from the point load to the point in equation. When the Boussinesq model is applied for soil, there is a tendency for the compressive stress in the soil to concentrate around the loading axis. This tendency becomes greater when the soil becomes more plastic due to increased moisture content or when the soil is less cohesive, such as sand. In view of this phenomenon, Frohlich introduced a concentration factor ν to Boussinesq's equations, for hard soil, $\nu = 3$, for normal soil $\nu = 4$, and for soft soil, $\nu = 5$ [5]. Other literature employs concentration factors for hard soil, $\nu = 4$, for normal soil, $\nu = 5$, and for soft soil, $\nu = 6$ [4, 6]. The concentration factor has been assumed to vary with the current soil density, the minimum density, and the maximum density of the soil material. An equation was developed to calculate the value of concentration factor.

$$\nu = 6 + (6 - 4)(P - P_{\min}) / (P_{\min} - P_{\max}) \quad (4)$$

where ν is the concentration factor, P is the current dry bulk density of the soil (g/cm^3), $P_{\max}$ is the maximum dry bulk density of the soil (g/cm^3), and $P_{\min}$ is the minimum dry bulk density of the soil (g/cm^3). Introducing the concentration factor, the vertical stress under the plate can be expressed in Cartesian coordinates as [6]

$$\sigma_z = \frac{\nu W z^\nu}{2\pi(r^2 + z^2)^{(\nu/2+1)}} \quad (5)$$

After the subsurface stress distribution is determined, soil strain (or compaction) is based on soil visco-elasto-plastic relationships. These relationships are to be defined for the

USCS terrain described in the terrain database. The constitutive (stress/strain) relationships for these soils are needed to define the soil response (sinkage) due to loading.

If bulk density, ρ , is plotted vs. $\log_{10}$ applied stress, σ_a , the relationship will be linear. During the compression procedure, soil particles will be rearranged and brought closer together. The straight line is also called the virgin compression curve, VCC, and the slope of that line is called the compression index, C [7]. If the soil has previously been subjected to a stress and a further stress is applied, the bulk density-stress relationship will increase along a line with a slight slope (secondary compression) until it joins with the VCC curve. The linear portion of the VCC in Figure 3 can be described by [7]

$$\rho = \rho_k + C \log_{10}(\sigma_a / \sigma_k), \quad (6)$$

where ρ is the computed bulk density, ρ_k is the density at a known stress σ_k , σ_a is the applied normal stress, and C is the slope of the line. If the VCC represents a dry soil, lines for soils at water contents less than saturation will be shifted to the left and parallel to the dry soil line. If the relationship in Eq. (6) is known for a given water content, or degree of water saturation, S_k , curves for other water contents can be computed from the following relationship [7]

$$\rho = [\rho_k + S_T (S_1 - S_k)] + C \log_{10}(\sigma_a / \sigma_k) \quad (7)$$

where S_T is the slope of the bulk density vs. degree of water saturation curve at a given stress, and S_1 is the desired degree of saturation. By predicting the bulk density variation due to repetitive normal loading, the soil element's vertical displacement can be determined along with the related net energy and power that must be applied to the mass. A soil element with a given height (H) has a vertical displacement (z) expressed by the following equation:

$$z = (1 - (\rho_0 / \rho_1)) \cdot H \quad (8)$$

where ρ_0 is the initial bulk density and ρ_1 is the final bulk density.

Power and Energy Calculations

Positive soil element vertical displacement occurs during compression when ρ_1 exceeds ρ_0 in Eq. (8). The required energy (E) to displace the soil element vertically (Δz) is calculated by the following equation:

$$E = F \cdot \Delta z = (\sigma \cdot A) \cdot \Delta z \quad (9)$$

where σ is the sub-surface normal stress, A is the soil element cross-sectional area in the horizontal plane. Equation (9) is

only applied in the model during compression (i.e. positive Δz). E is assumed to remain constant during rebound because the energy lost by the soil element is assumed to be negligible in the model. The power required during compression of the soil element in a given time interval (Δt) is determined by the following:

$$P = E / \Delta t \quad (10)$$

P is nonzero only when compression of the soil element occurs.

Repeated Vertical Loading

The time-dependent elastic and plastic properties of the soil are needed to fully describe the soil response to tire/track loads. Rebound properties are defined by the soil rebound index or measure of the decrease in density as the applied load is released. The time-dependent or viscous soil properties can be defined using a time constant of soil deformation.

The compression and rebound time constants, τ_c and τ_r , must be defined for the soil element and the values are indicators of the time required for the dependent variable ρ to change from the initial to the final value during compression and rebound. The following is the general form of the time-dependent compression and rebound factor of the model, respectively:

$$(1 - e^{t/\tau_c}), \quad (1 - e^{t/\tau_r}) \quad (11)$$

During compression, the change in bulk density is calculated by multiplying the theoretical change in bulk density determined from Eq. (7) by the time-dependent compression factor from the above expression. By doing so, the effect of the duration that a given normal load being exerted on the soil element is accounted for in the model. If a vehicle travels at a slower rate, the normal load is applied over a longer period of time; thus, the bulk density increase should be greater at a lower travel speeds. The time-dependent factor attempts to account for the time-dependent nature of a soil element's response to an applied normal load.

The rebound constant must also be predicted for the soil element. The value of the rebound constant is the amount of rebound that occurs when the calculated bulk density associated with the applied normal stress is less than the current density. If the bulk density increase is less than the rebound constant multiplied by two, the magnitude of the rebound in the model is estimated as half of the bulk density increase during compression. The rebound that occurs in a given time interval is also calculated by multiplying the time-dependent factor from above by the net rebound where t is equal to zero when compression of the soil element ends and rebound begins.