TerRA: Terramechanics for Real-time Application

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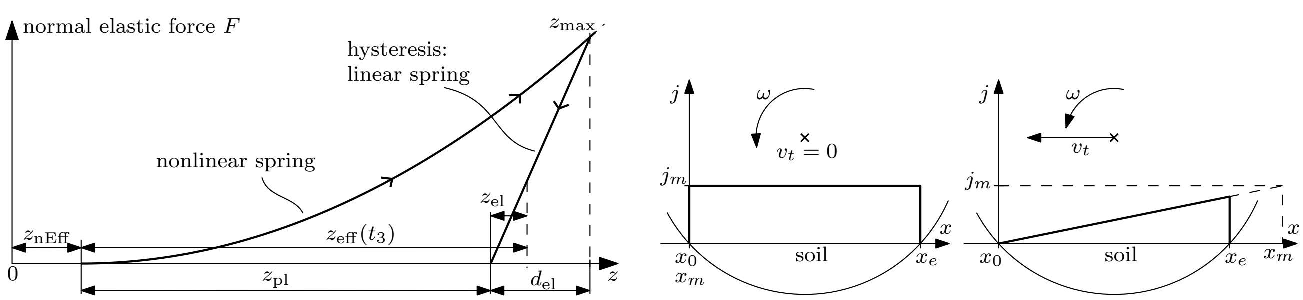
Wheeled mobile robots are very popular in planetary exploration due to their robust and energy-efficient mobility. Model-based control and observer algorithms can be implemented to further enhance these characteristics by exploiting the robots' over-actuation. The most challenging part of a required real-time capable model is the wheel-ground contact for sandy soil.

For wheel-soil contact in multibody simulations, semi-empirical models are most common although they do not consider the soil deformation explicitly. Since BEKKER's original theory [1] falls short on effects such as slip sinkage, lateral wheel and grouser forces, there are numerous extensions in literature, for a good overview see [2]. While most implementations feature an integration of normal and shear stress over the contact area of the wheel, [3] derived an explicit form for the use in real-time application. However, many researchers [3, 4] found that these semi-empirical models have considerable shortcomings which can only be solved by introducing and tuning additional parameters.

Motivated by the shown problems, the idea of this work is to develop a rigorously simple model that is tuned for a certain wheel-soil combination. It shall then be able to qualitatively and quantitatively cover important terramechanic effects for a use in control & observation algorithms as well as in simulation and optimization. This Terramechanics for Real-time Application (TerRA) features an elastoplastic model (inspired by [5]), novel dynamic sinkage and traction force calculations as well as a sinkage-dependent resistance force [1].

The normal force calculation is based on a nonlinear spring and damper. However, the deflection is not the full sinkage of the wheel. As can be seen in Fig. 1a, the total sinkage z is divided into an effective and a non-effective portion, z_{eff} and z_{nEff} respectively. While the latter is needed for the dynamic sinkage (see paragraph below), solely the effective sinkage is used for the force calculation. A linear elastic layer of thickness d_{el} is used to enable a steady state for any plastic sinkage. In addition to the shown spring force, there is a linear and a quadratic damping force acting on the rate of the effective sinkage $\dot{z}_{\text{eff}}$.



(a) Normal force calculation

(b) Shear length calculation for 100% slip (left) and moving wheel (right)

Fig. 1: Schematics of normal force and shear length in TerRA

The dynamic sinkage is explicitly calculated as in- and outward sinkage rate $\dot{z}_{\text{in}}$ and $\dot{z}_{\text{out}}$, respectively. $\dot{z}_{\text{in}}$ is known as *slip-sinkage* and is linearly dependent on the slip velocity and additionally depends nonlinearly on the total sinkage to prevent unrealistically large sinkage. As soon as the wheel moves tangentially to the ground, the plastic and non-effective sinkages are being reduced with the outward sinkage rate $\dot{z}_{\text{out}}$.

The tangential force for a wheel on soft soil consists of soil resistance due to sinkage and traction force which needs considerable shear deformation to be built up. WONG [1] describes the shear stress of a loose and dry non-cohesive sand as an exponential function of the shear length j which approaches its maximum, the MOHR-COULOMB shear stress. The problem of models that have no spatial soil discretization is that the shear length j cannot be integrated for individual soil areas. In TerRA, the slip velocity v_s is integrated to get the current maximal shear length j_m. Non-loaded soil comes in contact with the wheel for a tangential movement v_t, which is approximated by a shear length $j(x)$ that rises linearly to a point (x_m, j_m) and remains constant afterwards (see Fig. 1b). With the traction force containing the integral of the shear length over the contact patch, rising translational velocity (i.e. decreasing slip) leads to less traction force. To complete the tangential force calculation, a soil resistance force based on the passive earth pressure according to [1] is added.

Verification of qualitative effects in TerRA is shown for a single wheel scenario where the wheel is dropped into the sand, starts driving on level ground and subsequently hits an 8° and a 20° slope (see Fig. 2). At 0 s, the wheel immediately develops a plastic sinkage when hitting the ground, which is only reduced once the wheel starts moving translationally (2.5 s). It drives out of its indentation by reducing plastic and non-effective sinkage (2.5 s-7.5 s) and a steady state is reached. A certain slip is needed to built up the traction force which leads to a corresponding non-effective sinkage. Both increase on the 8° slope before the wheel hits the 20° slope and gets stuck. The described simulation of one wheel with TerRA runs roughly 100-times faster than real-time with a step size of 1 ms, i.e. one evaluation of the whole scenario takes about 10^{-5} s.

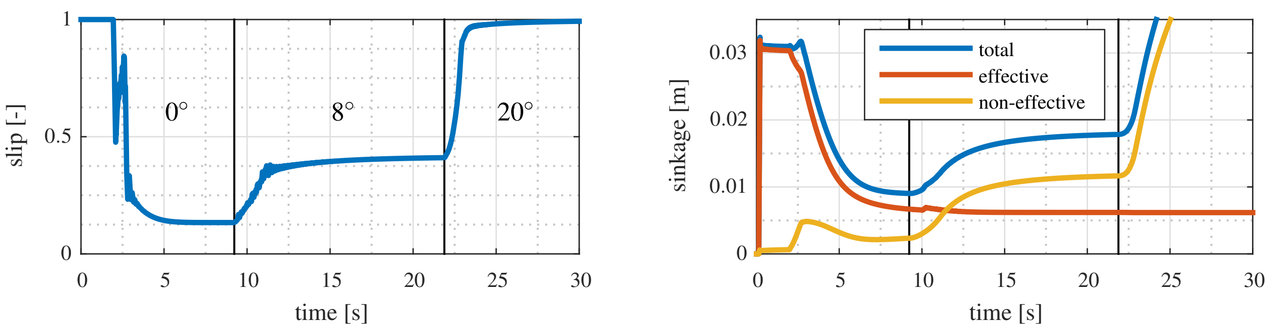


Fig. 2: Wheel slip (left) and sinkages (right) for verification scenario

The results show that despite its computational simplicity, TerRA is able to cover important effects of a dynamic wheel scenario qualitatively; a more in-depth analysis will be presented in the full paper. Future work will validate the model with single wheel tests and make use of this efficient yet capable TerRA model in on-board application such as [6] and multibody simulation and optimization [7].

References

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