Title: From Performance Optimization to Simulation-based Forensic Engineering – An extensive Approach for Dynamic Modeling of the HP³-Mole for InSight

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In order to enable the InSight's investigations of the Martian interior, the HP³-Mole has to hammer itself deeper below the surface of the red planet, than any other instrument before. In order to achieve this challenging goal, the dynamics of the impact driven locomotion as well as the mutual influence between the stroke cycle and the regolith need to be well understood. However it is not possible to observe the complex mechanism behaviour while the HP³-Mole is operating in Martian soil or terrestrial simulants. Thus numerical models are used to predict the dynamic behaviour on Mars. Given the different environmental conditions on Mars, these models need to be independent from any calibration under terrestrial conditions. To meet these demands, an enhanced multibody dynamics model of the inner hammering mechanism is coupled to several tiers of models for the regolith. The latter range from simple analytical models based on Rankines soil pressure theory, to very detailed particle based models using the Framework DEMETRIA.

One of the most important applications of the model is to understand the effects of the mechanism's interaction with the surrounding regolith. By covering both, mechanism and soil dynamics it is possible to observe soil deformation fields as well as the mechanism motion profiles at the same time. The gathered knowledge has been used in order to understand principle effects like e.g. wave propagation phenomena due to the impact driven locomotion. These detailed models can be used to study and understand the behaviour during operation phase. Additionally gained insights on the soil behaviour will also be useful in order to analyze and understand the actual conditions present on Mars by using data measured during the operation phase of the mechanism.

As a big variety of measurements or prototypes are not realizable within the schedule and budget of low-cost missions, these virtual prototypes of the locomotion system also enabled the multi-criterial optimization of the hammering mechanism in order to meet the demands on penetration depth, durability and the friction based operational principle. As virtual prototypes also allow for damage free failure investigations, the models were applied to forensic engineering, i.e. the identification of failure causing points in the operational cycle. Using this technique it was possible to track down failure points in prototype mechanisms and thus to enhance the design without having to build or damage further prototypes. This approach can also be used to check flight-hardware and to identify the reason for possible non-conformance behaviour.

The proposed technique for extensive virtual prototyping enables faster and more reliable designs in low-cost planetary exploration missions. The developed regolith models are also ready to be applied in future missions, enabling locomotion beneath as well as on planetary surfaces.