Project Summary

Identification and Significance of Innovation

The liberation of dust and debris particles caused by rocket plume flow from spacecraft landing on the unprepared regolith of the Moon, Mars, and other celestial bodies poses one of the highest risks facing robotic and human exploration activities. Regolith debris is lofted from the surface by the gas flow and accelerated to high velocities with kinetic energy levels that pose a threat to the vehicle itself and any nearby sensitive objects. The Apollo 12 Lunar Module landing near the Surveyor 3 spacecraft provided testimony of the risks with the Surveyor spacecraft sandblasted with regolith grit. Lunar rover missions are planned as part of the Google Lunar X-Prize competition, including visits to the Apollo landing sites on the Moon. The spray of regolith particles from the landings could damage those sites and seriously degrade their scientific and historical value. Significant soil erosion levels and deep cratering will occur for any future human exploration because of larger landers requiring multi-engine clusters at higher thrust levels and the eventual need for repeated launch and landing operations.

The proposed research will result in a novel multi-physics simulation system with tremendous gains in physics modeling fidelity. The proposed development will overcome significant hurdles in the capabilities of current CFD simulations to describe the motion of realistic, rather than idealized, granular particle systems. The implication of this advance in CFD capability goes well beyond NASA applications and the severe problems associated with cratering and particle liberation. Non-spherical particles pervade the energy, chemical, agricultural, mining and pharmaceutical industry. The unique and innovative features of the proposed simulation environment will be the following:

- High-resolution computations of plume impingement flow and seamless mixed rarefied-continuum flow transitions through a wide spectrum of Mach and Knudsen numbers.
- Realistic granular material flow modeling for unsteady cratering and soil particle flow prediction
- Resolution of all physics details through Eulerian-Eulerian two-phase simulations with Adaptive Mesh and Algorithm Refinement (AMAR) technique.
- Assembly of all the physics models for a unified multi-disciplinary simulation platform. Modular implementation of each element for easy future upgrades and transportability.

The proposed simulation package will furnish exploration system developments with a unique tool for a wide array of space exploration scenarios, including:

- Prediction of soil erosion during space vehicle landing and launch operations
- Prediction of debris and dust transport and sand-blasting effects on sensitive hardware components
- Mitigation of debris environment through lander propulsion architecture trade-offs between number of engines, spacing, angle, engine shut-down elevation, landing approach flight path
- Aid in designing dust and debris mitigation measures such as berms, deflectors, paved landing pads, etc.

The proposed simulation tool will provide valuable insights for the Space Exploration community towards addressing fundamental uncertainties regarding the impact of particle debris and dust liberation.

Technical Objectives and Work Plan

The overall objective of this work is to develop a comprehensive multi-phase flow modeling framework based on the Eulerian-Eulerian approach with adaptive mesh refinement capabilities. In Phase I the feasibility of the proposed Eulerian-Eulerian multi-phase flow approach has been demonstrated. Specific objectives of the Phase I included the following:

1. Demonstrate the ability of the UFS multi-phase flow simulation software to properly model the gas-granular multi-phase flow physics in response to rocket plume gas impingement utilizing DEM-derived granular constituent models
2. Develop process of formulating arbitrary irregular particle shape constituent models from first principle Discrete Element Method (DEM) modeling
3. Develop process of formulating constituent models for arbitrary size distribution effects
4. Develop approach for integration of granular flow multi-phase Eulerian simulation system in exiting UFS continuum-rarefied flow solver framework
5. Perform assessment of the integrated simulation tool against experiments.

Technical Accomplishments

All technical objectives of Phase I have been accomplished by the STTR team. The major achievements include:

1. A powerful framework for modeling gas-granular flows in extreme environments has been further developed with parallelization and solution-adaptive meshing capabilities.
2. The Eulerian-Eulerian multi-phase flow framework is applied to dense granular flows where methods like DEM are often prohibitively expensive.
3. Constitutive models were derived from DEM simulations for non-spherical particles and the trends in granular stresses were reproduced in the Eulerian-Eulerian framework.
4. The approach to extend the entire framework to non-spherical as well as polydisperse formulations was developed and demonstrated in this work.

Results show a highly successful Phase I effort with a significant potential payoff in the Phase II, where models can be further developed and refined to be applied in production environment.s

Potential NASA Application(s):

The debris simulation tool will offer a powerful simulation capability of first order importance to the Space Exploration Program for robotic and human mission architecture definition to the Moon, Mars, and other destinations. The highest risks occurring during propulsive landing and takeoff of spacecraft require gas-granular flow simulation capabilities for designing mitigation measures. The granular flow modeling capability will be equally important for modeling regolith material manipulation for In-situ Resource Utilization such as pneumatic transport, granular flow movement in excavators, resource extraction systems moving and conveying planetary regolith, as well as processing of regolith in reactors for resource extraction.

Potential Non-NASA Application(s):

Many potential non-NASA commercial applications exist in civil and military industries. Dust, sand and snow stir-up during helicopter landing and take-off in a desert or arctic environment result in severe visibility impairment (brown-out) and danger of debris ingestion. Civil engineering and environmental engineering applications include wind-borne landscape erosion and dust transport to populated areas