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SOIL MOISTURE AND HEAT TRANSPORT MODELING TO SUPPORT SIMULATION OF INFRARED IMAGING

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ABSTRACT

A virtual testing capability was built to explore the performance of infrared sensors in complex natural and man-made environments. These environments may contain irregular ground surfaces, multiple soil types, surface vegetation, roads, and exposed and buried rocks and other objects [2]. This numerical toolbox attempts to represent faithfully all processes that significantly affect an infrared sensor image. A key component of the energy balance is heat emitted or absorbed by the soil. For imagery, only the behavior at the surface of the scene is of interest. But, heat transport must be modeled in three dimensions to capture the surface expression of subsurface heat transport processes. A soil's thermal properties depend on its moisture content, requiring that hydrologic processes be simulated as well. Moisture and thermal energy movement in the soil are computed with the ADH (Adaptive Hydraulics/Hydrology Model) [4].

ADH is a spatially adaptive, continuous Galerkin, finite element model that simulates partially-saturated flow and heat transport in three-dimensional soils (or other materials), coupled to two-dimensional surface water flow on a face of the soil [3]. Moisture movement through the soil is estimated by approximating Richards' equation on tetrahedra

$$S_S S(\psi)\frac{\partial \psi}{\partial t} + \eta \frac{\partial S\left(\psi\right)}{\partial t} = \nabla \cdot \left[K_S k_r\left(\psi\right) \nabla \left(\psi + z\right)\right] + W, \tag{1}$$

where ψ is pressure head, S_S is the specific storage, which accounts for water compressibility and aquifer elasticity, $S\left(\psi\right)$ is the water saturation or volumetric fraction of pore space occupied by water, η is the porosity or volumetric void fraction, K_S is the water-saturated hydraulic conductivity, k_r is the relative permeability of the media, and W is a source/sink term. Both S and k_r are functions of ψ. K_S and S_S are provided as data. Boundary conditions may be known pressures (derived from known groundwater table elevations) or known fluxes (like infiltration from rainfall). The solution of Richards' equation produces fields of pressure and moisture content. ADH also approximates surface

water equations (diffusive wave or full shallow water) to simulate runoff, puddle development, and infiltration. Surface water solution gives water depth and velocity fields. Presently, the groundwater and surface water equation sets exchange explicit, elemental fluxes at each time step. Other processes, including subsurface phase change, distributed moisture uptake within the root zone, and flow through macropores and cracks, are being added.

An energy balance equation to simulate heat conduction, convection, and surface heat exchange was added to the soil moisture model of the original ADH

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c)_f \, \mathbf{v} \cdot \nabla T = \nabla \cdot (K_T \nabla T) + q_m, \tag{2}$$

where ρ is density, c is specific heat, T is temperature, $\mathbf{v}$ is fluid velocity, K_T is thermal conductivity, and q_m is a source of energy. Specific heat and thermal conductivity depend on the soil moisture. Surface heat exchange includes short-wave input, long-wave input, long-wave emitted, sensible heat, latent heat, and precipitation heat [1]. Hydrologic and meteorologic boundary conditions for the models are derived from weather stations located at each field test site. An energy-budget ray caster (described in another presentation) converts meteorologic data into heat transport boundary conditions for the soil model, accounting for surface orientation and shadows generated by objects in the scene. The ray caster also collects multi-spectral energy reflected and emitted from the soils and other objects for processing by the sensor model into a synthetic image.

This numerical toolbox produces realistic synthetic images that match field-collected images both in resolution and complexity. Moreover, quantitative comparison of the magnitude and variation of intensities in synthetic and field-collected images is encouraging. The simulated imagery is helping predict sensor performance under a variety of weather and vegetation conditions, thereby providing guidance on optimal times-of-day and conditions to see contrast in the images. To date, several hundred images have been produced and analyzed, providing a basis for improving automated image processing algorithms. Recent applications have explored the variability of infrared imagery in desert and temperate settings under wet and dry conditions. The resulting images show remarkably different contrast during and shortly after rainfall events, compared with dry conditions. A toolbox of simulators like this permits exploration of the interplay between these fine-scale process and the sensing physics as observed from coarser scales common to remote sensing. It also provides an idealized environment for evaluating the benefits of using multiple sensors of different spectra simultaneously (sensor fusion), while avoiding many practical issues encountered in field testing, like georegistration.

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