High-Fidelity Modeling to Support Route Clearance

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ABSTRACT

Route clearance teams must combine experience and intuition with other available data (including anomalies in sensor imagery) to identify and neutralize threats. Non-threat features in sensor imagery, often called 'clutter', tend to cause false alarms. Target discrimination is confounded by scene complexity, changing weather conditions, and image quality degradation from atmospheric effects, sensor platform dynamics, and sensor electronics and optics.

High-fidelity, physics-based numerical models may be used to describe moisture and energy transport processes and atmospheric and sensor effects, thus producing synthetic sensor imagery with sufficient detail and appropriate character to train target discriminators and support combat maneuver operations and route clearance. Synthetic images are produced at likely choke points for a variety of target types, placement techniques, sensor vantage points, times of day, and weather conditions. This work supports tabletop exercises (TTX) to explore the relative value of different information sources in the route clearance process.

Because modeling is relatively fast and inexpensive, it is a logical tool to help adapt detection strategies rapidly as threats evolve in a hybrid conflict. It can also speed up concept development and experimentation by helping identify feasible alternatives and by narrowing the focus of physical experiments – even helping screen novel sensing concepts.

1.0 INTRODUCTION

Movement of troops from one location to another is an important and common occurrence in modern deployment. Strategically it is crucial to move the troops safely, quickly, and efficiently. Safety is the primary concern when selecting a route to be followed. Route planning is done in advance, and route clearance teams are used to detect and neutralize any potential hazards. Route reconnaissance with sensors is one of the options used by route clearance teams. Due to unconventional warfare in the recent past, troop movements have been severely hampered by various kinds of hazards that include Improvised Explosive Devices (IEDs), roadside threats, and suicide bombers. These potential hazards require greater vigilance, which increases the time required to move troops. They may be forced to take alternate routes, travel at reduced speeds, and also have a route clearance team that can identify and neutralize potential threats to the convoy in advance. Route clearance teams have several tools available to identify these threats. One of these options is to use airborne or vehicle mounted electro-optical and infrared (EO/IR) sensors that provide imagery to the team. The teams then must combine experience and intuition with other available data (including anomalies in sensor imagery) to identify and neutralize threats. Non-threat features in the sensor imagery, often called ' clutter', tend to cause an increase in false alarm rates (FARs). Target discrimination is confounded by scene complexity, changing weather conditions, and image quality degradation from atmospheric effects, sensor platform dynamics, and sensor electronics and optics. Hence, training the route clearance teams is needed to properly identify potential threats, reduce false alarms, and increase the probability of threat detection (P_d). This will help increase the efficient movement of troops. These teams can be trained to detect spatial or geometric anomalies and EO/IR sensor based spectral anomalies [3]. Sensor imagery is needed for training the route clearance teams during TTXs. This imagery can be obtained by deploying real sensors along a route. The main drawback of this method is the limitation of training the team along a route for which sensor imagery is available. This would limit the training data set to the complexities of the environment and climatic conditions for which training imagery data are available. It also limits the imagery to the time of the day for which real sensor imagery is collected. It is highly impractical and very expensive to collect different kinds of sensor imagery for various climatic conditions, at different times of the day, and for different complex environmental conditions. As an alternative to field collected imagery, synthetic imagery can be used during TTX for training the route clearance teams. This synthetic imagery although not real, appears like imagery that is produced by a sensor. This will help enhance the threat detection capabilities by increasing the P_d and reduce FAR.

High fidelity, physics based numerical modeling is a cost effective method to produce synthetic imagery. These physics-based numerical models may be used to describe moisture and energy transport processes and atmospheric and sensor effects, thus producing synthetic sensor imagery with sufficient detail and appropriate character to train target discriminators and support combat maneuver operations and route clearance. As modeling is relatively fast and inexpensive, it is a logical tool to help adapt detection strategies rapidly as threats evolve in a hybrid conflict. It can also speed up concept development and experimentation by helping identify feasible alternatives.

2.0 NUMERICAL MODELING

The U.S. Army Engineer Research and Development Center (ERDC) has developed a near surface computational test bed (CTB) to help understand the effects of geophysical phenomena on signatures sensed by various sensors operating in the electro-magnetic (EM) spectrum. The CTB produces 3-D, physics-based, high-fidelity numerical modeling simulations of the geo-environment using highly parallelized codes running on high performance computing (HPC) machines [2]. This suite of physics based models of CTB include Adaptive Hydrology (ADH) soil model [5], the vegetation model that computes radiative transfer in plants [7], the Quick

Caster (QC), which is an energy-based ray caster responsible for energy propagation within a scene [4], and the EO/IR sensor model [6]. Sensor modalities modeled include Near-IR, Visible, mid-wave infrared (MWIR), long-wave infrared (LWIR), and very long-wave infrared (VLWIR) bands.

This modeling capability can be used to predict and improve the performance of current and future sensor systems for surface and near-surface anomaly detection amid highly heterogeneous and complex environments. The ideal synthetic scenes produced by these simulations are sampled by sensor models that represent passive and active sensor modalities. These sensor models produce synthetic imagery, which can then be used during the TTX of route clearance teams.

2.1 Data Requirements

For each named area of interest (NAI), the CTB typically requires topography data to generate a volumetric mesh, soil properties, spectral properties, vegetation (location, type and size), and weather data. The sensor parameters for the sensor of interest are also needed for the simulations. The volumetric meshes are generated from a point cloud that can be obtained from a digital elevation model (DEM) of the area, from light detection and ranging (LIDAR) data, or from photogrammetry data. Vegetation model meshes are built based on their size and type and are placed on the volumetric mesh based on their location. This is generally accomplished by extracting locations from an image or overlaying the image on the top surface of the volumetric mesh. Spectral properties such as reflectance and emissivity of the soil are needed by the CTB. Soil properties like porosity, hydraulic conductivity, thermal conductivity (dry and saturated), specific heat, and specific gravity are needed by the soil models. These can be measured if soils are available, or estimated from soil texture estimates. The weather data including solar zenith, solar azimuth, air temperature, wind speed, wind direction, precipitation, short wave radiation, and long-wave radiation are also needed for CTB simulations. Sensor models require parameters including field of view (FOV), Modulation Transfer Function (MTF), wavelength and focal length. The chosen sensor type may dictate other sensor parameters.

ERDC has collected data from several geo-specific sites for modeling and simulations of several regions of the world. The data from these sites, geo-typically represent about 60% of the world climatic zones. These data can be used as surrogate sites for some of the more common sites. Physical data collection is not an absolute requirement for modeling and simulation tasks and to produce synthetic imagery. Other sources of data like digital elevation models (DEMs) of the region, satellite imagery and weather data from a surrogate site can also be used for modeling. However, a physical data collection will produce more realistic synthetic imagery.

2.2 Soil Moisture and Heat Transport Model

ADH is a finite element model that simulates partially saturated flow and heat transport in three- dimensions for soils and other materials. It is also coupled to a model for two-dimensional surface water flow on the surface of the soil mesh. The ground water and surface water exchange explicit elemental fluxes during a given time step. The surface heat exchange includes short-wave input, long-wave input, long-wave emitted, sensible heat, latent heat, and precipitation heat. The boundary conditions for the model are computed using meteorological data and, when available, results from the QC model. The ADH model produces soil moisture and temperature fields.

2.3 Vegetation Model

The vegetation model is needed to understand the role of the energy budget components in a canopy-soil system. Vegetation is modeled as discrete elements over the soil mesh. Variations of the energy budget for the discrete vegetation elements are described in terms of the net radiation (*Rn*), sensible (convective) (*H*) and latent heat

(*LE*), and ground heat fluxes (*G*). The energy budget is given in Equation 1.

$$\mathrm{Rn} - \mathrm{LE} - \mathrm{H} - \mathrm{G} = 0 \quad (1)$$

Temporal variations of sensible and latent heat fluxes are modeled as a function of vertical position of the discrete vegetation element by linking the latent and sensible heat fluxes to the measured wind speed and relative humidity. The profile of near-surface wind and relative humidity is based on an empirical model driven by the measured wind and humidity. Solving the energy budget for each element at each time increment provides information on the spatial and temporal variation of vegetation element temperature, latent heat flux, and sensible heat flux. The latent heat modeled as Equation 2

$$LE = \frac{l(Tv)(r_v^* - h_a r_a^*)}{(r_s - r_a)} \quad (2)$$

is coupled to the observed wind speed and relative humidity and is dependent on vapor density (r^*_v) and aerodynamic resistance (r_a). The latent heat also depends on the air density at a specified humidity $(h_a r^*_a)$, the saturation vapor density in the canopy (r^*_v), and the element layer modeled stomatal resistance (r_s). The stomatal resistance sub-model is approximated using air temperature, relative humidity, global radiation, and vegetation type. The sensible heat is modeled as Equation 3

$$\mathrm{H} = \mathrm{r_a C_p (T_l - T_a)/R_a} \quad (3)$$

where T_l is the leaf temperature, $\mathrm{r_a}$ is the air density, C_p is the specific heat of air at constant pressure, and $\mathrm{T_a}$ is air temperature from measurement.

2.4 Energy-based Ray Casting Model

The QC tool is used to produce large-scale high-fidelity, ideal synthetic thermal and RGB color images. It is a parallelized program that can handle large domains containing more than a half-billion facets. The QC uses the facet geometry of a domain in a finite element mesh format as input, along with the material properties of the surface materials. The material properties include reflectance, emittance, and transmittance values by spectral band for a given material. The QC currently uses six spectral bands, and the spectral input properties can be controlled for each band. Wavelengths of the input bands can also be controlled. In addition, QC uses the meteorological data to compute shadows.

2.5 Sensor Model

The EO/IR sensor model applies atmospheric effects, imaging geometry, and sensor response to the ideal radiance image produced by the QC to produce an image that simulates what a particular EO/IR sensor would produce. Atmospheric transmission parameters are generated separately by MODerate resolution atmospheric TRANsmission (MODTRAN) [1], the industry-standard atmospheric model.

The sensor model performs spatial re-sampling of the ideal image based on the resolution and field-of-view parameters of the sensor and the flight profile parameters selected for the simulation. The re-sampled image is convolved with the modulation transfer function (MTF) to represent the optical effects of the simulated sensor. The MTF can be either measured using the actual sensor, if it exists, or calculated based on sensor characteristics such as diffraction, detector spacing, etc. MTFs are calculated using the Night Vision Integrated Performance

Model (NV-IPM) from the Night Vision and Electronic Sensors Directorate (NVESD). The sensor model also simulates detector response, digitization effects, and sensor noise to produce the final simulated sensor image.

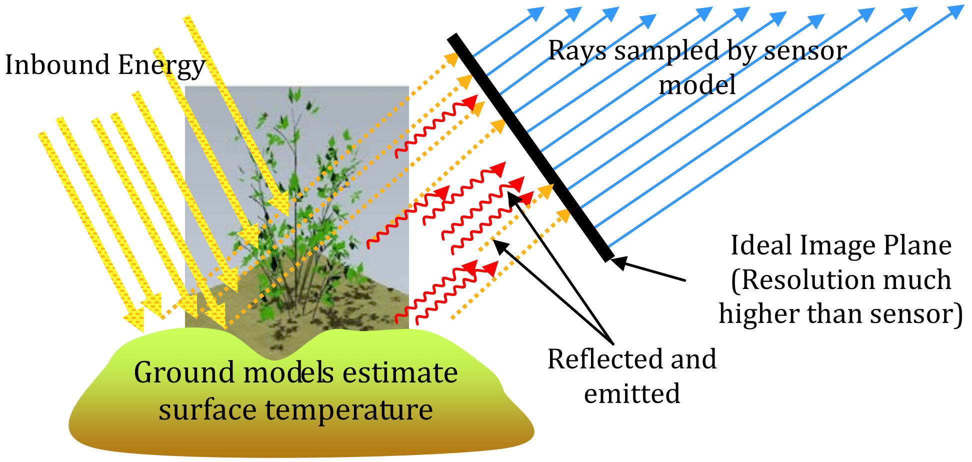

Figure 1: Diagram of the energy budget in the CTB.

3.0 MODEL APPLICATION

The CTB models use high-performance computing to conduct simulations of various environments. Applications to date have mainly simulated arid outdoor environments, but current research is accommodating different climates and urban environments. All CTB models communicate with each other during execution and pass data between the models. The QC generates the energy based on the time of the day and sun angles obtained from the meteorological data. The ADH model and the vegetation model use the fluxes or energy generated by the QC and produce temperatures for the ground surface and vegetation in the scene.

The most important feature of the QC is consideration of shadows cast by the vegetation in the scene. Fluxes for these areas are computed automatically based on visibility of the ground surface to the light source. Temperature in the shadowed ground surface is accurately computed during day and night time. The QC then uses these temperatures, computes the in-band radiance using Planck's equation, and produces an ideal RGB and thermal images for a given time of the day.

The EO/IR sensor model takes this ideal image as input and applies the MTF, blur, and atmospheric effects and produces a sensor image. It can also produce an apparent temperature image. The MTF can be changed based on the sensor that is being simulated. The resulting sensor images from the sensor model can be used to train the route clearance teams during TTX. This process can be repeated to produce sensor images at different times of the day. It can also be repeated with different weather data information to produce synthetic imagery for different geo-environmental conditions. This modular approach allows the CTB to simulate different sensors mounted on different platforms in a wide variety of terrain types and environmental conditions.

3.1 Roadside Disturbed Soil

Figures 2 and 3 show a typical roadside scene. The domain is about 30 m by 30 m in plan view and extends 1 m below the ground surface. Figure two shows the domain with the soil colored light brown and vegetation models colored green. Figure 3 shows physical temperature contours for early afternoon with warmer being red and cooler, blue.

Figure 4 contains a synthetic imagery from both a mid-wave infrared sensor (left) and a long-wave infrared sensor (right). The sensor look angle is nadir and the field of view is approximately 11 m by 15 m. The scene contains two small volumes of disturbed soil, but no targets. Disturbed soil normally has a lower porosity and different reflectance than undisturbed soil. Changes in bulk density of the soil cause changes to the thermal and hydrologic response. Together, the thermal and spectral effects often make disturbed soil visible in imagery. In Figure 5, the same scene is viewed from a different position using the same long-wave infrared sensor, but at two different times of day.

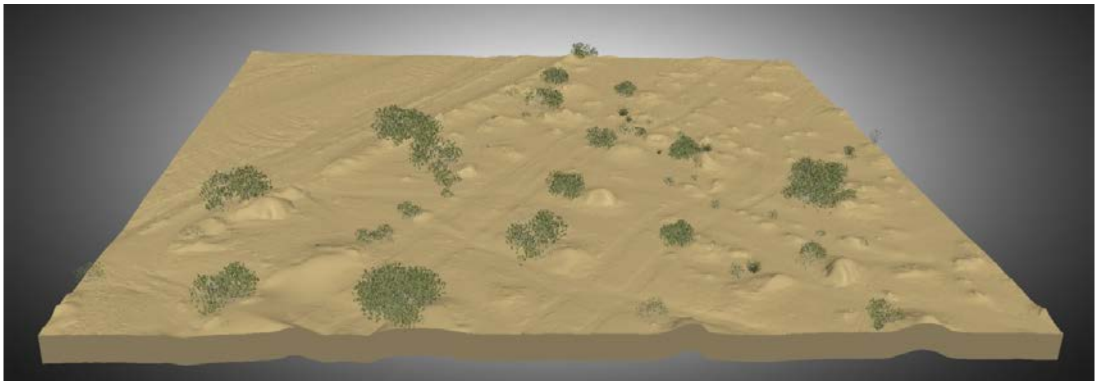

Figure 2: Volumetric model of a site next to a route.

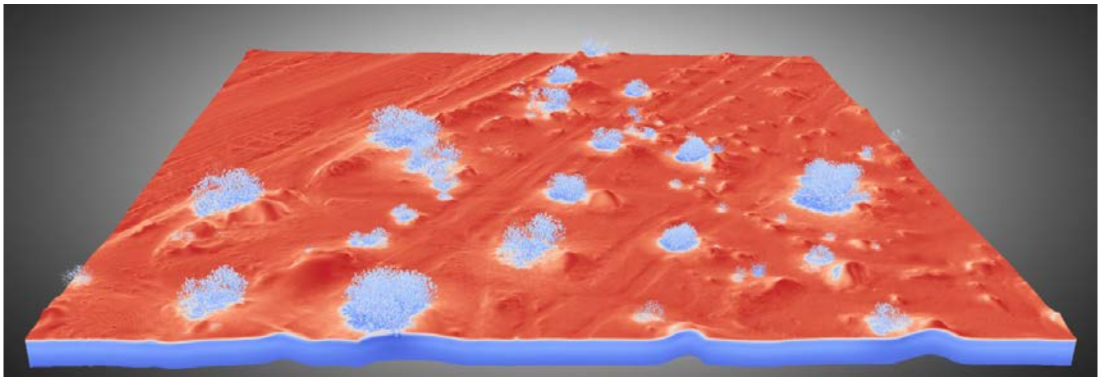

Figure 3: Temperature distribution in the model

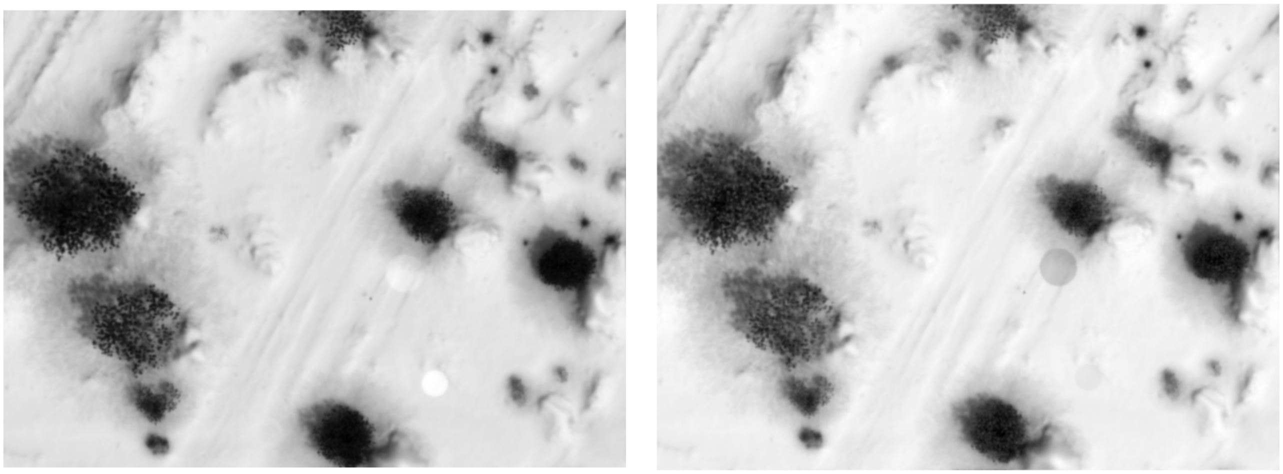

Figure 4: MWIR image (left) and LWIR image (right) showing targets next to the route at 10 AM

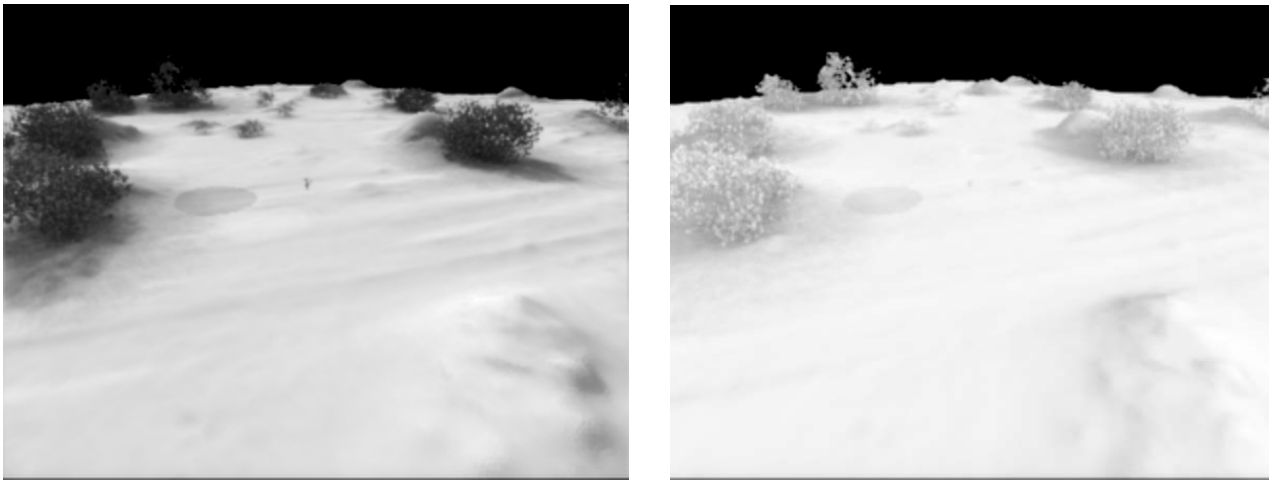

Figure 5: LWIR images from a ground-based platform at 0900 (left) and 1600 (right) local time.

3.2 Route Clearance

Presently, these same simulation tools are being applied to the problem of route clearance. The models can produce synthetic imagery from any proposed sensor and location, allowing users to explore the relative value of sensor types and platforms. In this example, the user is computing the benefit of having an aerial sensor platform ahead of the convoy versus only handheld and ground vehicle mounted. Figures 6 shows imagery from an area of interest on a test route within the United States. Figure 7 shows an initial surface of a simulation model domain for this site. The domain is 50 m by 50 m in plan view. Figure 8 gives the same simulation domain from a different perspective and Figure 9 gives a closer, side view of the computational mesh. The soil model is three dimensional, extending 1 m below the ground surface. The domain need not be deeper because these simulations only extend over a few weeks. The diurnal variability of temperature in the soil extends less than 50 cm and seasonal thermal effects are not being considered in this case. Because no meteorological station was deployed at this location, the models were driven with downscaled weather data available worldwide. Figure 10 gives sample synthetic MWIR imagery for this roadway both with and without a volume of disturbed soil. The resolution in the image matches that of a currently fielded sensor of interest.

Figure 6: Aerial photo of an area of interest.

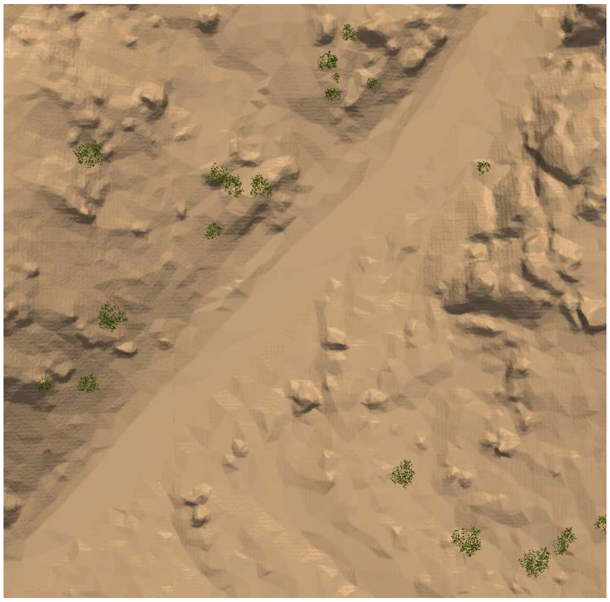

Figure 7: Aerial view of the model.

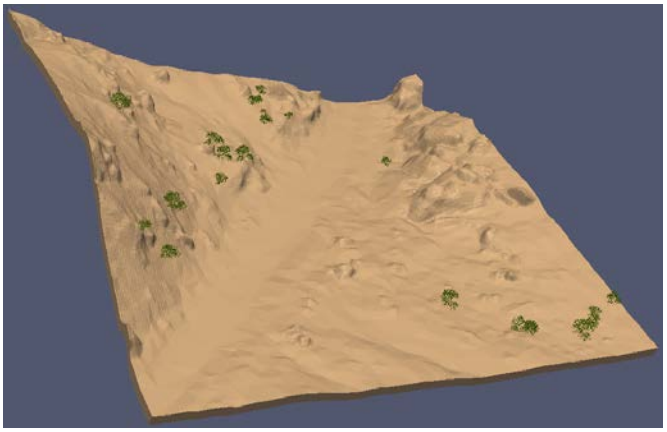

Figure 8: Three-dimensional model showing topography and vegetation along the route.

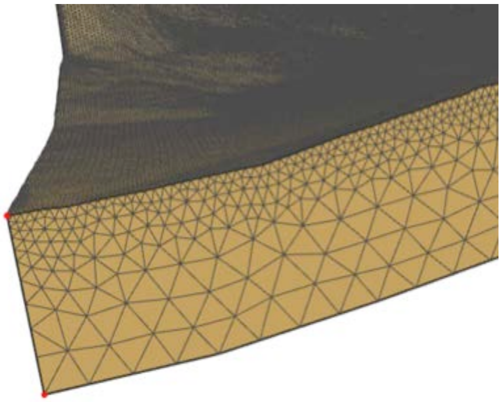

Figure 9: Side view of the computational mesh showing higher resolution near the ground surface.

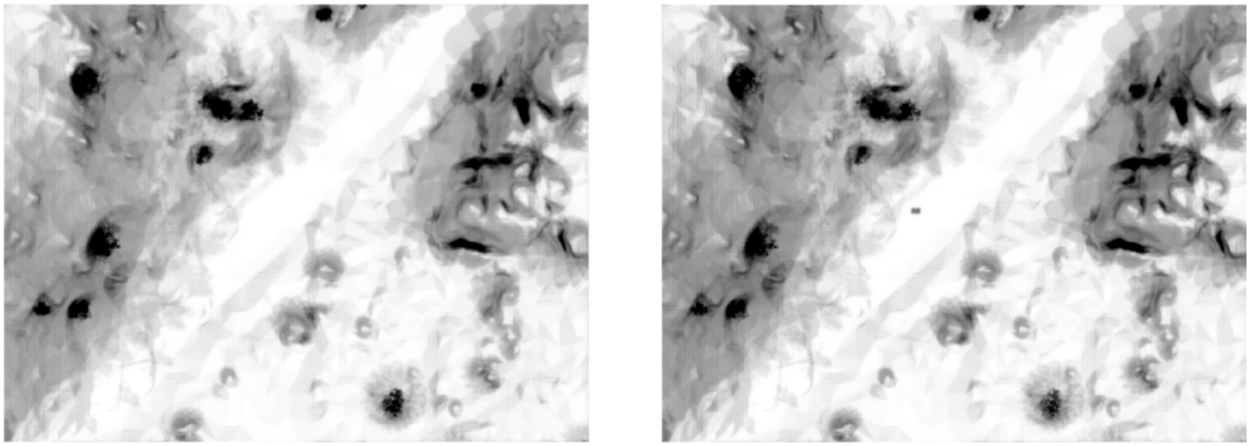

Figure 10: MWIR image of the route at 10 AM without disturbed soil (left) and with disturbed soil (right).

4.0 CONCLUSION

Synthetic imagery from modeling can be used as a supplement to real sensor imagery. It can also be used to aid decisions on sensor deployment during troop movements. The CTB can be used to produce synthetic imagery with and without targets and also for different kinds of targets at different depths. This helps to train the route clearance teams to look for different kinds of anomalies during the evaluation of the actual sensor imagery. It is a cost effective way to produce imagery for different kinds of environments, different kinds of sensors, different sensor platforms and different times of day. It is useful during training exercises of route clearance teams. As shown in the above images, not all anomalies are visible at all times. Detection of anomalies depends on the time of the day, sensor type, and site conditions.

5.0 REFERENCES

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