Numerical Terrain Modelling for Wireless Underground Sensor Networks
A Prototype for Nut Tree Plantations

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Abstract—Underground terrain poses a highly intricate and challenging environment to the propagation of waves carrying information from sensor to the sink nodes. Due to the complexity and level of detail, it is often difficult to realistically model such an environment for conducting tests. However, using numerical methods, the environment characteristics could be translated to a compatible framework, for testing complex networking models such as Wireless Underground Sensor Network (WUSN). Such transformation should lend the necessary clarity and simplicity required for effective problem analysis. In this paper, we demonstrate this possibility using the typical underground terrain environment for nut tree plantations, basing the field data on a full-fledged commercial pecan farm. The results shown are introductory to ongoing research on the effective use of such numerical methods for maximum power efficiency and bit rate for distributed WUSN, and optimum water usage in irrigation control. This paper forms a sequel to previous related research publications.

Keywords-component; Wireless Underground Sensor Network (WUSN); Distributed Sensing; terrain modelling; Digital Elevation Model (DEM); numerical methods; nut tree plantation; MATLAB

I. INTRODUCTION (HEADING 1)

Underground environment poses unprecedented challenges to the propagation of data from source to sink wireless nodes [1], [2]. In order to circumvent such challenges, many alternatives have been proposed to Electromagnetic (EM) waves for propagation of data among wireless sensor nodes [3]. Even among such viable alternatives, the Wireless Underground Sensor Network (WUSN) design and deployment are influenced by the vagaries of the underground terrain [4].

The problem of realistically modelling underground terrain has been subject to study in recent years, in the context of various application scenarios [5], [6]. Such studies underscore the complexity involved in realistic modelling. It could be fairly assumed that the simulation of wireless propagation of underground data based on realistic terrain model should be complex as well.

Recent research has examined the problem of wireless propagation of data underground [7], [8], [9]. However, a generic approach to modelling both the terrain and aspects of wireless data propagation underground has been lacking.

This research is aimed at bridging this gap, by means of proposing such a generic model, which

- models the underground terrain using numerical methods for clear and simple analysis of the problem of wireless data propagation among nodes
- is flexible enough to accommodate vagaries of the underground terrain that impact WUSN deployment, including distributed sensing environments
- enables analysis of the wireless data propagation for the specific underground terrain, in order to determine the most ideal WUSN deployment strategy for optimal power efficiency and bit-rate, and optimal usage of scarce water resource for better irrigation practices

This paper presents a proof-of-concept of the terrain modelling using numerical methods, and the corresponding simulation results using MATLAB. This paper is linked to, and is a sequel to previous related research publications [10], [11].

Section 2 briefly re-introduces the scope of the project from the previous publications. Section 3 details the concepts and the algorithms involved in the numerical terrain modelling. In Section 4, the results of simulation using MATLAB have been presented. Section 5 discusses the results. Section 6 concludes the paper.

II. SCOPE

A. Deployment Terrain

The WUSN designed and developed as part of this project is intended to be deployed underground a large commercial pecan farm. The farm area under consideration is around several hundred hectares, with a total tree population ranging in several tens of thousands. The tree distribution pattern is in accordance with the typical requirements of pecan tree spacing for maximum yield [12]. The farm is subject to average to
intense aboveground seasonal activity, including movement of harvesting machines transporting crops from the trees.

B. Sensing Requirements

The underground sensors would be relied upon to accurately sense and report soil moisture data for clusters of planted trees across different layers of the soil (light, medium and heavy), under all climatic conditions. The soil moisture data for each cluster needs to be reported to a remote data and replenishment.

The soil moisture content is an important parameter in the classification of clusters of plants in the farm. Under all climatic conditions, the soil moisture content should be monitored to ensure adequate moisture for the growth of the crops. The soil moisture content can be determined using various methods, including gravimetric methods, tensiometric methods, and electrical conductivity methods.

C. Network Requirements

The WUSN has to be cost-effective on a sustained basis, and ideally should be self-sufficient, including power replenishment. In addition, the WUSN should not be impacted by the extremities of the environment. There is no mobility expected of the nodes in the network.

III. NUMERICAL TERRAIN MODELLING

The terrain model has been envisaged in terms of two distinct characteristics:

- terrain attributes
- soil properties

A. Terrain Attributes

The model has considered a total land area of 100 hectares, in keeping with the typical size of a large nut tree farm [13]. The total area has been classified in terms of units of 1 hectare each, adapted from the typical plantation paradigm [14]. A grid scale of 1:10 has been adopted for modelling the unit. Thus a unit covering a land area of 100 m² (square meters) x 100 m² has been represented using 1-10 X and Y units on the grid scale.

Since the feeder roots of a pecan are found at the upper 12 inches of the soil [12], the sensor nodes need to be deployed in an elevation range of 0-30 cm. This range has been classified into three layers of 10, 20 and 30 cm elevation respectively, for the approximation of primary terrain attributes. The equations for approximating the first and second derivatives of the Digital Elevation Model (DEM) for the grid cell (i,j) [15], and the corresponding equations for the primary terrain attributes [16] except Aspect, have been listed under TABLE II.

Considering the elevation range, the Slope values should be infinitesimal. Since gentle Slope values could contribute to large spikes in Aspect angles [17], the value of Aspect angle has been restricted to the range 0-90 degrees by means of the adapted algorithm [18] listed under TABLE III.

In TABLE III, S_{FDWE} denotes the Slope value in the West-East direction, and S_{FD-SN} denotes the Slope value in the South-North direction. Since the elevation range of 0-30 cm has been defined for the topsoil region, the elevation gradient is essentially in the South-North direction, and hence the Slope gradient (> 0) should be as well, as per TABLE II. Consequently, the value of Aspect should be 0 as per TABLE III.

From TABLE II and TABLE III, it should be evident that all the primary terrain attributes are dependent on the elevation z and the grid cell size d.

The primary terrain attributes considered for the model, adapted from [19], have been listed under TABLE I.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Definition</th>
<th>Hydrologic Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>Elevation</td>
<td>Climate, vegetation type, potential energy</td>
</tr>
<tr>
<td>Slope</td>
<td>Gradient</td>
<td>Overland and subsurface flow velocity and runoff rate</td>
</tr>
<tr>
<td>Aspect</td>
<td>Slope azimuth</td>
<td>Solar irradiation</td>
</tr>
<tr>
<td>Profile Curvature</td>
<td>Slope profile curvature</td>
<td>Flow acceleration, erosion/deposition rate</td>
</tr>
<tr>
<td>Plan Curvature</td>
<td>Contour curvature</td>
<td>Converging/diverging flow, soil water content</td>
</tr>
</tbody>
</table>

TABLE II. EQUATIONS

\[
\frac{x_z}{d} \equiv \frac{(z_{i+1,j} - z_{i,j})}{2d} \\
\frac{x_y}{d} \equiv \frac{(z_{i,j+1} - z_{i,j})}{2d} \\
\frac{x_{xx}}{d^2} \equiv \frac{(z_{i+1,j} - 2z_{i,j} + z_{i-1,j})}{d^2} \\
\frac{x_{yy}}{d^2} \equiv \frac{(z_{i,j+1} - 2z_{i,j} + z_{i,j-1})}{d^2} \\
\frac{x_{xy}}{4d^2} \equiv \frac{(z_{i+1,j+1} - z_{i+1,j-1} - z_{i-1,j+1} + z_{i-1,j-1})}{4d^2} \\
\]

\[
[x_z^2 + x_y^2]^{1/2} \text{ The formula used for calculating Slope [16].} \\
\left( x_{xx} x_z^2 + 2x_x x_z x_y + x_{yy} x_y^2 \right) / \left( S_{FD}^2 (x_z^2 + x_y^2 + 1)^{1/2} \right) \text{ The formula for calculating Profile Curvature [16]. Here } S_{FD} \text{ denotes Slope.} \\
\left( x_{xx} x_z^2 - 2x_x x_z x_y + x_{yy} x_y^2 \right) / S_{FD}^3 \text{ The formula for calculating Plan Curvature [16]. Here } S_{FD} \text{ denotes Slope.} \\
\]

TABLE III. ALGORITHM FOR CALCULATING ASPECT ANGLE

\[
\text{if } S_{FD-SW} = 0 \text{ AND } S_{FD-NE} = 0 \text{ Aspect = undefined} \\
\text{else if } S_{FD-W} = 0 \text{ AND } S_{FD-SH} < 0 \text{ Aspect = 180} \\
\text{else Aspect = 0} \\
\]
B. Soil Properties

The soil properties have been assumed to display covariance across a range of 10 hectares. This concept is akin to that of a *pedotransfer functions (PTFs)* [20]. The range has been based on the pecan farm characteristics and is custom, and can be varied according to different field requirements. The grid scale adopted is similar to that of the terrain attributes, viz., 1:10. However, in this case, each grid scale should represent a land area of 10 hectares, considering the total land area of 100 hectares.

TABLE IV reproduces the range of soil physical properties as listed under Table 2.3 of [21]. The topsoil model has been based on these properties and their corresponding range of values.

<table>
<thead>
<tr>
<th>Soil Physical Property</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Density ($\rho_p$)</td>
<td>2.6-2.8</td>
<td>Mg/m$^3$</td>
</tr>
<tr>
<td>Dry Bulk Density ($\rho_d$)</td>
<td>0.7-1.8</td>
<td>Mg/m$^3$</td>
</tr>
<tr>
<td>Porosity ($f$)</td>
<td>0.03-0.7</td>
<td>Fraction, m$^3$/m$^3$</td>
</tr>
<tr>
<td>Air Porosity ($f_a$)</td>
<td>0-0.7</td>
<td>Fraction, m$^3$/m$^3$</td>
</tr>
<tr>
<td>Void Ratio ($e$)</td>
<td>0.4-2.2</td>
<td>Fraction</td>
</tr>
<tr>
<td>Gravimetric Soil Moisture Content ($\omega$)</td>
<td>0-0.3</td>
<td>Fraction, kg/kg</td>
</tr>
<tr>
<td>Volumetric Soil Moisture Content ($\theta$)</td>
<td>0-0.7</td>
<td>Fraction, m$^3$/m$^3$</td>
</tr>
<tr>
<td>Degree of Saturation ($s$)</td>
<td>0-1</td>
<td>Fraction</td>
</tr>
<tr>
<td>Dry Specific Volume ($V_d$)</td>
<td>0.5-1</td>
<td>m$^3$/Mg</td>
</tr>
<tr>
<td>Air Ratio ($\alpha$)</td>
<td>0-1</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>Liquid Ratio ($\theta_l$)</td>
<td>0-1</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>Wet Bulk Density ($\rho_b$)</td>
<td>1-2</td>
<td>Mg/m$^3$</td>
</tr>
</tbody>
</table>

C. Modelling Algorithm

The topography of the farm has been modelled as a combination of terrain attributes and soil properties. The unit of classification of the topography has been fixed as 1 hectare, adapted from typical plantation paradigm [14]. The elevation of the topography has been modelled for the topsoil region of 0-30 cm [8], in layers of 10cm gradation. The primary terrain attributes have been approximated for each layer as a function of both the elevation and the corresponding grid cell size (*vide* TABLE II). A grid scale of 1:10 has been adopted for modelling the unit. Thus a unit covering a land area of 100 m$^2$ (square meters) x 100 m$^2$ has been represented using 1-10 X and Y units on the grid scale.

Since the grid cell size does not vary across layers, the primary terrain attributes at higher layers have been modelled as *covariant* with the lowest layer (0-10 cm layer).

The terrain attributes are assumed to be consistent across the topography, modelled as *concatenations* of the unit (1 hectare); this assumption stems from the fact that the elevation and grid cell size do not vary for such a model.

The soil properties have been modelled to exhibit covariance across every ten hectare topographical area, based on the pecan farm characteristics. This has been modelled by choosing a random value within the applicable range (*vide* TABLE IV) for each soil property.

For both the terrain and soil properties, mean values of the applicable range of values have been calculated to study and record the degree of covariance.

IV. SIMULATION AND RESULTS

Simulations were implemented and tested using MATLAB for both terrain and soil properties of the topographic model.

A. Terrain

For simulating the terrain properties, a unit area of 1 hectare has been considered, since the properties do not vary across the topographic area for a *concatenation* model as stated above. TABLE V lists the mean values calculated for the three significant primary terrain attributes (*vide* TABLE I), viz., Slope ($S_{10}$), Profile Curvature ($K_P$), and Plan Curvature ($K_I$), across the three elevation layers of 10, 20 and 30 cm respectively. The equations listed under TABLE II were used in the calculation.

<table>
<thead>
<tr>
<th>Elevation (in cm)</th>
<th>Slope ($S_{10}$)</th>
<th>Profile Curvature ($K_P$)</th>
<th>Plan Curvature ($K_I$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.7953</td>
<td>0.4296</td>
<td>-1.3141</td>
</tr>
<tr>
<td>20</td>
<td>0.9457</td>
<td>0.1970</td>
<td>-0.6202</td>
</tr>
<tr>
<td>30</td>
<td>1.0466</td>
<td>0.1872</td>
<td>-0.5996</td>
</tr>
</tbody>
</table>

* Positive curvature values are concave upward and are characterized by accelerating and converging flows [15].

Figure 1 depicts the 3D surface mesh-grid of the terrain generated using MATLAB, with the mean values listed under TABLE V.

In Figure 1, the X-axis denotes the Slope ($S_{10}$), the Y-axis denotes the Profile Curvature ($K_P$), and the Z-axis denotes the Plan Curvature ($K_I$) for the three covariant elevation layers of 10, 20 and 30 cm respectively.

B. Soil

The soil properties remain the same across each unit (1 hectare) under consideration for the topography, only their values exhibit covariance. Accordingly, in addition to using random values in range (*vide* TABLE V) to simulate the soil properties for each unit, the notion of a *Mean Index Value (MIV)* has been introduced to ascertain the degree of covariance across every 10 hectare area (or a *concatenation* of 10 units). The MIV has been calculated as the mean of all the corresponding soil properties for 10 concatenated units. Since the individual soil properties display covariance across each *concatenation*, the same covariance should also be reflected in their MIVs.
TABLE VI lists the MIVs for the range of the total distance of 100 hectares, in gradients of 10 hectares (or a concatenation of 10 units), along with the grid scale.

<table>
<thead>
<tr>
<th>Mean Index Value (MIV)</th>
<th>Land Area (in hectares)</th>
<th>Grid Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45903128939119</td>
<td>100000</td>
<td>1</td>
</tr>
<tr>
<td>0.65942679545304</td>
<td>200000</td>
<td>2</td>
</tr>
<tr>
<td>0.576044445996784</td>
<td>300000</td>
<td>3</td>
</tr>
<tr>
<td>0.64402270514004</td>
<td>400000</td>
<td>4</td>
</tr>
<tr>
<td>0.529385781172339</td>
<td>500000</td>
<td>5</td>
</tr>
<tr>
<td>0.560493957315548</td>
<td>600000</td>
<td>6</td>
</tr>
<tr>
<td>0.560016169357162</td>
<td>700000</td>
<td>7</td>
</tr>
<tr>
<td>0.615482409020533</td>
<td>800000</td>
<td>8</td>
</tr>
<tr>
<td>0.657685420984897</td>
<td>900000</td>
<td>9</td>
</tr>
<tr>
<td>0.501817252281566</td>
<td>1000000</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2 depicts the 3D surface mesh-grid of the terrain generated using MATLAB, with the MIVs listed under TABLE VI.

V. DISCUSSION OF RESULTS

The results validate the simulation objectives and concepts in the following aspects:

1. A simpler interpretation of the underground topography can be achieved using numerical approach than a realistic approach.
2. The modelling achieved using numerical approach can be discrete in accordance with the field conditions, as in the case of a realistic approach.
3. The numerical approach enables a highly simplistic visual representation and evaluation of the complex field data without loss of fidelity, as evinced in Figure 1 and Figure 2.
4. Often, the essence inherent to numerous correlated and complex minute field data elements can very well be captured by a simple high-level compact logical representation, without any loss of generality. The use of a Mean Value Index (MIV) in the simulation is a case-in-point.

The results of the simulation bear significance in relation to modelling data propagation among sensor nodes in the underground environment. The simple and clear-cut interpretation of data afforded by the numerical approach as evinced by the simulation and its results can be fundamental to solving problems related to distributed sensor data propagation in the underground, by means of both EM waves and its viable alternatives. These experiments and their results would be shared in a future paper.

VI. CONCLUSION

This paper highlighted the concept, the algorithms and the preliminary simulation results using MATLAB of numerical underground terrain modelling, for the purpose of examining...
the larger problem of the impact of the terrain on data propagation among sensor nodes, using both EM waves and its viable alternatives. The simulation results showed how complex aspects of the underground terrain can be rendered simplistically using numerical approach, without compromising on the relevant accuracy of the data. The preliminary results highlighted in this paper would be expanded to address the problem of data propagation in distributed sensing in future publications. Such optimality of power, space and data flow in distributed sensing has the potential to totally eliminate wastage of precious water in smart irrigation using Wireless Underground Sensor Networks (WUSN).

REFERENCES


