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 control center bordering the farm. This data would be used to adequately regulate the watering of the Pecan trees, as per the crop requirement [12].

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 m^2 (square meters) x 100 m^2 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, $S_{FD\text{-}WE}$ denotes the *Slope* value in the *West-East* direction, and $S_{FD\text{-}SN}$ 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 I. PRIMARY TERRAIN ATTRIBUTES

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

TABLE II. EQUATIONS

Formula	***Description***
$z_x \cong {(z_{i+1,j} - z_{i-1,j})}/{2d}$ $z_y \cong {(z_{i,j+1} - z_{i,j-1})}/{2d}$ $z_{xx} \cong {(z_{i+1,j} - 2\, z_{i-1,j} + z_{i-1,j})}/{d^2}$ $z_{yy} \cong {(z_{i,j+1} - 2\, z_{i,j} + z_{i,j-1})}/{d^2}$ $z_{xy} \cong {\left(\begin{matrix} z_{i-1,j+1} - z_{i+1,j+1} + z_{i,j-1} - \\ z_{i-1,j-1} + z_{i+1,j-1} \end{matrix}\right)}/{4d^2}$	These formulae [15] have been used for approximating the first and the second derivatives of DEM for a grid cell (i,j). Here *z* denotes the primary terrain attribute *Altitude* listed under TABLE I, and *d* denotes the grid cell distance. The value of *Altitude* corresponds to the elevation of the particular layer. These approximated values have been used in the calculation of the other primary terrain attributes listed under TABLE I, except *Altitude* and *Aspect*.
$\left[{z_x}^2 + {z_y}^2\right]^{1/2}$	The formula used for calculating *Slope* [16].
${(z_{xx}z_x^2 + 2z_{xy}z_xz_y + z_{yy}z_x^2)}/{\left[S_{FD}^2\, (z_x^2 + z_y^2 + 1)^{3/2}\right]}$	The formula for calculating *Profile Curvature* [16]. Here S_{FD} denotes *Slope*.
${(z_{xx}z_y^2 - 2z_{xy}z_xz_y + z_{yy}z_x^2)}/{{S_{FD}}^3}$	The formula for calculating *Plan Curvature* [16]. Here S_{FD} denotes *Slope*.

TABLE III. ALGORITHM FOR CALCULATING ASPECT ANGLE

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if $S_{FD-WE} = 0$ AND $S_{FD-SN} = 0$
        Aspect = undefined

else if $S_{FD-WE} = 0$ AND $S_{FD-SN} < 0$
        Aspect = 180

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 function*s *(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 IV. RANGE OF SOIL PHYSICAL PROPERTIES

Soil Physical Property	***Range***	***Units***
Particle Density (ρ_s)	2.6-2.8	Mg/m^3
Dry Bulk Density (ρ_b)	0.7-1.8	Mg/m^3
Porosity (f_t)	03-0.7	Fraction, m^3/ m^3
Air Porosity (f_a)	0- f_t	Fraction, m^3/ m^3
Void Ratio (e)	0.4-2.2	Fraction
Gravimetric Soil Moisture Content (w)	0-0.3	Fraction, kg/kg
Volumetric Soil Moisture Content (Θ)	0-0.7	Fraction, m^3/ m^3
Degree of Saturation (s)	0-1	Fraction
Dry Specific Volume (V_b)	0.5-1	m^3/ Mg
Air Ratio (α)	0-1	Dimensionless
Liquid Ratio (θ_p)	0-1	Dimensionless
Wet Bulk Density (ρ'_b)	1-2	Mg/m^3

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_{FD}), Profile Curvature (K_p), and Plan Curvature (K_c), across the three elevation layers of 10, 20 and 30 cm respectively. The equations listed under TABLE II were used in the calculation.

TABLE V. MEAN VALUES FOR COVARIANT TERRAIN ATTRIBUTES

Elevation (in cm)	***Slope (S_{FD})***	***Profile Curvature (K_p)***	***Plan Curvature (K_c)***
10	0.7953	0.4296	-1.3141*
20	0.9457	0.1970	-0.6202
30	1.0466	0.1872	-0.5996

* Positive curvature values are concave upward and are characterized by decelerating 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_{FD})*, the Y-axis denotes the *Profile Curvature (K_p)*, and the Z-axis denotes the *Plan Curvature (K_c)* 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.

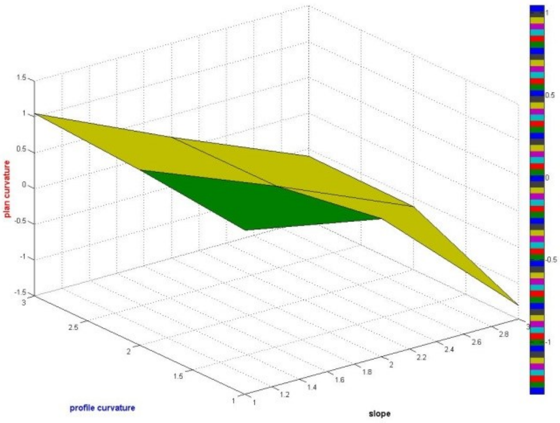

Figure 1. 3D surface mesh-grid of covariant unit terrain attributes

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 VI. MEAN INDEX VALUES FOR COVARIANT SOIL PROPERTIES

Mean Index Value (MIV)	***Land Area (in hectares)***	***Grid Scale***
0.459003128939119	100000	1
0.659426779545304	200000	2
0.576044445996784	300000	3
0.644402270514004	400000	4
0.529385781172339	500000	5
0.560493957315548	600000	6
0.560016169357162	700000	7
0.615482409020533	800000	8
0.657685420984897	900000	9
0.501817252281566	1000000	10

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

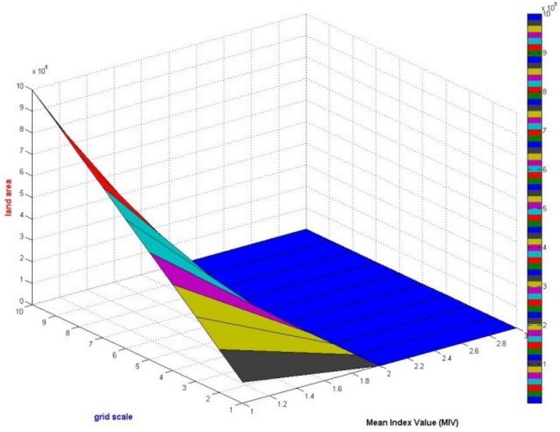

Figure 2. 3D surface mesh-grid of covariant topographic soil properites

In Figure 2, the X-axis denotes the *Mean Index Value (MIV)* for each covariant 10 hectare distance (or a *concatenation* of 10 units), the Y-axis denotes the *grid scale,* and the Z-axis denotes the total *land area* in gradients of 10 hectares.

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 optimal 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

[1] Akyildiz, I. F., & Stuntebeck, E. P. (2006). Wireless underground sensor networks: Research challenges. Ad Hoc Networks, 4(6), 669-686.

[2] Vuran, M. C., & Akyildiz, I. F. (2010). Channel model and analysis for wireless underground sensor networks in soil medium. Physical Communication, 3(4), 245-254.

[3] Sun, Z., & Akyildiz, I. F. (2010). Magnetic induction communications for wireless underground sensor networks. Antennas and Propagation, IEEE Transactions on, 58(7), 2426-2435.

[4] Sun, Z., & Akyildiz, I. (2013). Optimal Deployment for Magnetic Induction-Based Wireless Networks in Challenged Environments.

[5] Santamaría-Ibirika, A., Cantero, X., Salazar, M., Devesa, J., & Bringas, P. G. (2013, October). Volumetric Virtual Worlds with Layered Terrain Generation. In Cyberworlds (CW), 2013 International Conference on (pp. 20-27). IEEE.

[6] Yang, W., & Wu, S. (2013, November). Data Modeling and Visualization of Guangzhou Underground Space. In *Information Technology and Applications (ITA), 2013 International Conference on* (pp. 343-347). IEEE.

[7] Jayaram, M. N., & Venugopal, C. R. (2014, January). Modeling-Simulation of an Underground Wireless Communication Channel. In Proceedings of International Conference on Internet Computing and Information Communications (pp. 81-91). Springer India.

[8] Silva, A. R., & Vuran, M. C. (2009). Empirical evaluation of wireless underground-to-underground communication in wireless underground sensor networks. In *Distributed Computing in Sensor Systems* (pp. 231-244). Springer Berlin Heidelberg.

[9] Bogena, H. R., Huisman, J. A., Meier, H., Rosenbaum, U., & Weuthen, A. (2009). Hybrid wireless underground sensor networks: Quantification of signal attenuation in soil. Vadose Zone Journal, 8(3), 755-761.

[10] Parameswaran, V., Zhou, H., & Zhang, Z. (2012, December). Irrigation control using wireless underground sensor networks. In Sensing Technology (ICST), 2012 Sixth International Conference on (pp. 653-659). IEEE

[11] Parameswaran, V.; Zhou, H; Zhang, Z. ((2013, December) Wireless underground sensor network design for irrigation control: Simulation of RFID deployment. In Sensing Technology (ICST), 2013 Seventh International Conference on (pp.842-849). IEEE.

[12] Andersen, P.C. and T.E. Crocker. (2008) The pecan tree. Univ. of FL EDIS publication HS 982. (17 pp). Retrieved from http://edis.ifas.ufl.edu/hs229

[13] Australian Macademias. (2012). 2007 Benchmarking report - The Australian macadamia industry 2009 to 2012 seasons Project: MC09001 Retrieved from http://www.australian-macadamias.org/item/6646-latest-benchmarking-report-released

[14] Tree Plantation (2002). Nut Trees. Retrieved from http://www.treeplantation.com/nut-trees.html

[15] Mitášová, H., & Hofierka, J. (1993). Interpolation by regularized spline with tension: II. Application to terrain modeling and surface geometry analysis. Mathematical Geology, 25(6), 657-669.

[16] Erskine, R. H., Green, T. R., Ramirez, J. A., & MacDonald, L. H. (2007). Digital elevation accuracy and grid cell size: Effects on estimated terrain attributes. Soil Science Society of America Journal, 71(4), 1371-1380.

[17] CARTER, J. R. (1992). The effect of data precision on the calculation of slope and aspect using gridded DEMs. Cartographica: The International Journal for Geographic Information and Geovisualization, 29(1), 22-34.

[18] Hodgson, M. E. (1998). Comparison of angles from surface slope/aspect algorithms. Cartography and Geographic Information Systems, 25(3), 173-185.

[19] Moore, I. D., Grayson, R. B., & Ladson, A. R. (1991). Digital terrain modelling: a review of hydrological, geomorphological, and biological applications. Hydrological processes, 5(1), 3-30.

[20] Grunwald, S. (2005). What do we really know about the space-time continuum of soil-landscapes? In Grunwald, S. (Ed.). *Environmental soil-landscape modeling: Geographic information technologies and pedometrics*. (pp. 3-36). Boca Raton, FL, USA: CRC Press.

[21] Lal, R., & Shukla, M. K. (2004). *Principles of soil physics*. CRC Press.