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Slope Gradient and Vehicle Attitude Definition Based on Pitch and Roll Angle Measurements: A Simplified Approach

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Abstract: Simplified models relating pitch and roll angle measurements of a roving vehicle to terrain slope and vehicle attitude were developed. The simplified models are based on previously published models by Rowe and Spencer [1] and Yang et al. [2]. These simplified models are easier to implement using microcontroller technology reducing the number of trigonometric function calculations, improving program execution and simplicity. Simulated and field tests were conducted comparing published and simplified models. In a simulated test, agreement between models showed coefficient of correlation (r) results of 0.999 ($p<0.05$). Mean absolute deviation between models was less than 0.12° for slope gradient, and 0.51° for vehicle attitude. In a field test models were programmed in a microcontroller, a clinometer was used to obtain pitch and roll measurements of a roving ATV. Terrain slope results derived from pitch and roll measurements were compared to results derived from high accuracy GPS readings. Slope gradient results showed high coefficient of correlation, low absolute error and high model efficiency. Slope aspect results showed correct aspect classification more than 85% of the time.

Keywords: Slope measurement, vehicle attitude, euler angles, modeling, soil slope.

INTRODUCTION

According to Euler's theorem, any rotation may be described by three angles: pitch, roll and yaw. Rowe and Spencer [1] showed that measurements of pitch (α) and roll (β) angles of a tractor could be used to determine ground slope (θ) and vehicle attitude (ψ) thus:

$$\sin\theta = \left(\sin^2\alpha + \sin^2\beta\right)^{1/2} \tag{1}$$

$$\sin\psi = \sin\beta \Big/ \left(\sin^2\alpha + \sin^2\beta\right)^{1/2} \tag{2}$$

More recently, Yang *et al.,* [2] modified the models initially developed by Rowe and Spencer. Yang proposed that ground slope (θ) and vehicle attitude (ψ) based on pitch (α) and roll (β) angles be calculated according to the following equations:

$$\cos\theta = \left(1 \Big/ 1 + \tan^2\alpha + \tan^2\beta \right)^{1/2} \tag{3}$$

$$\tan\psi = \frac{\tan\beta \big/ \tan\alpha \times \left(1+\tan^2\beta\right) + \tan\alpha \times \tan\beta}{\left(1+\tan^2\alpha + \tan^2\beta\right)^{1/2}} \tag{4}$$

The models developed by Rowe and Spencer and Yang *et al.,* contain several trigonometric functions. Implementing such models using microcontroller technology can be challenging since trigonometric functions require extensive repetitive calculations. The objective of this research was to simplify existing models and to test if simpler models could be used to calculate ground slope and vehicle attitude based on pitch and roll measurements. The basic assumption for this simplification is the limitation on the magnitude of the pitch and roll angles being measured since soil slope of croplands have a relatively small range.

The limitation in slope gradient of arable lands is shown on the National Resources Inventory (NRI), a statistical survey of land use and natural resources conditions and trends on U.S. non-Federal lands. The NRI groups soils according to their potential and limitations for sustained production of the commonly cultivated crops. Limitations are classified and progressively numbered from I to IV [3]. According to the 1997 NRI survey, 152,307,151 hectares of non-Federal rural land are used as cropland in the United States [4]. It is estimated that 94.7% (144,234,873 hectares) of the referred cropland have slope gradient less than 16.7° (30%). Table **1** lists the classification of the cropland by capability class. In fact, the notion that the majority of the cropland is usually located on gently sloping ground is reinforced by the Land Capability Classification of the British Society for Soil Science. In such system, 11 to 15° is the assumed upper limit for agricultural equipment operation such as combines and 2-wheel drive tractors [5]. Therefore 15° to 16° can be regarded as a soil slope boundary limit that very seldom will be exceeded for production agricultural

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operations. A boundary limit of 15° was used for all analysis in this study.

Table 1. Non-Federal Rural Land Distribution According to Capability Class

Class	Area (ha)	% of Total	Slope Gradient
I	10,732,987	7.0	Nearly level (0 - 3%)
II	70,679,962	46.4	Gentle slopes (1 - 8%)
III	46,445,052	30.5	Moderately steep slopes (10 - 20%)
IV	16,393,270	10.8	Steep slopes (20 - 30%)

The literature indicates that the measurement of pitch and roll angles of a roving vehicle can be regarded as a possible mean of soil slope definition [6, 1, 2]. It is therefore safe to assume that neither pitch nor roll will ever exceed the proposed limit of 15° when the soil slope being estimated is also within this limitation. Taking this limit into account, results of sine and tangent calculations as contained in both published models are not significantly different than a first order approximation. Soil gradient slope (θ) and vehicle attitude (ψ) models that are based on pitch (α) and roll (β) angles can therefore be simplified to

$$\theta = \sqrt{\alpha^2 + \beta^2} + \varepsilon \quad (5)$$

$$\psi = \tan^{-1}\frac{\beta}{\alpha} + \varepsilon \quad (6)$$

where ε is an error term representing the estimated difference between results using these simplified models with the published models.

MATERIALS AND METHODS

A simulated and a field test were conducted to test the accuracy of the proposed simplified models when compared to models previously published.

Simulated Test

To determine the magnitude of the error term (ε) associated with the simplified models, simulated pitch and roll angles were used in the estimation of slope gradient and vehicle attitude using Matlab®. Pitch and roll angles were bound by ± 15°. Results obtained with the simplified models were compared with those obtained with existing published models. Indices used in the assessment of the error term were:

Mean Absolute Deviation (MAD). MAD is calculated as:

$$MAD = \frac{1}{n}\sum_{i=1}^{n} ABS\left(X_i - XX_i\right) \quad (7)$$

where X_i - XX_i represents the difference between models' results when using the same pitch and roll angles.

The correlation coefficient (r) between results.

Vehicle attitude results were expressed in radians, and bounded by ± π. Therefore the combinations of positive and (or) negative pitch and roll angles put the measurement in one of four possible quadrants. To convert the results to degrees (0-360), a conversion algorithm was used. The algorithm is defined in Table **2**, along with the assumed convention for pitch and roll results.

Table 2. Algorithm Used for Vehicle Attitude Correction

Quadrant	Pitch	Roll	I[a]	II[b]
First	-	+	Ψ[c]	ABS(Ψ)
Second	+	+	180 – Ψ	180 – Ψ
Third	+	-	180 – Ψ	180 – Ψ
Fourth	-	-	360 + Ψ	360 – Ψ

[a]Algorithm used to correct results of the Rowe and Spencer model.
[b]Algorithm used to correct results of both Yang and simplified models.
[c]Calculated vehicle attitude.

Field Test

A data acquisition system (DAS) using a dual-axis clinometer (Schaevitz sensors, model ACCUSTAR II) and a microcontroller (Basic Atom, Basic Micro) was built and programmed to measure pitch and roll angles of an all-terrain vehicle (Kawasaki Mule, model 2510). Extensive documentation about this system was previously reported [7]. The assumption used in the design of the DAS was that axial measurements are the result of both differences in terrain elevation and vehicle's vibration. The DAS was mounted on a bracket attached to the roll cage cross member of the ATV.

The ATV was driven through a 4.4 hectare pasture field of the University of Tennessee Experiment Station in Blount County. The field has natural variable topography, and it is formed by deep, well-drained soils in a Cumberland-Dewey-Huntington soils series association. Average vehicle speed during testing was 4 m/s. A swath width of 2 meters was used in order to collect spatially intensive data. The combination of vehicle speed and swath width yielded a pitch and roll measurement for every 4 m^2.

While collecting vehicle axial data, a centimeter-accuracy, dual-frequency RTK-GPS was used to collect high-resolution elevation data for a digital representation of the surface area (Trimble, model AgGPS 214). A second dual-frequency RTK-GPS was used as a base station to compute error correction codes (Trimble, model MS 750). These codes were transmitted to the rover unit via a 900 MHz radio link (Trimble, model Trimtalk 900).

Dual-axis sensor data collected during field testing represent the variation of pitch and roll angles of the vehicle as it traveled the field's surface. The sensor has a built-in low pass filter (0.25 Hz at -3 dB) therefore no additional filtering was required. After data were collected, a spatial-domain filter was applied by averaging data points in the spatial resolution of 100 m^2. The chosen spatial resolutions represent highly detailed field measurement scale 1: 1575 (100 m^2).

Slope Aspect Calculation

To calculate slope aspect, vehicle attitude and vehicle heading are needed. Linear regression models were used to determine vehicle heading by using ten 10-second samples of GPS coordinates, which was found to be 137º. Detailed explanations about this technique can be found at Yang *et al.,* [2].

Benchmark Measurements

The benchmark chosen to evaluate measurement accuracy was slope data derived from an elevation surface of the test site created from high-resolution RTK-GPS points. This surface was created using Universal Kriging, a statistical interpolation method commonly used in the geosciences. A total of 32,564 highly-accurate elevation points were collected during the field test. Half of these points were randomly chosen and used in the surface creation, while the remaining half was used in a jackknife procedure to verify the quality of the interpolation process. In the jackknife procedure, estimated elevation values are compared with collected points which were left out of the interpolation. A low mean absolute error (MAE) in this procedure means that a true digital representation of the original surface was achieved. The calculated MAE for the benchmark surface was 2.79 10^{-2} m.

Confident that the estimated surface accurately portrays the test area, terrain attributes were calculated using standard equations for slope determination. For the proposed spatial resolution (100 m²), the average elevation differences were sampled in the Northing (y) and Easting (x) directions.

Indices Used in Measurement Comparisons

Three indices were used in the comparison of measurements of slope gradient against the benchmark:

- Coefficient of determination (r^2). The confidence interval (CI) of the coefficient of determination was calculated using Fisher's transformation.
- Mean Absolute Error (MAE)
- Model Efficiency (ME). The ME method developed by Nash and Sutcliffe is used to compare model results to observed values [8]. ME values can range from - ∞ to 1. The closer the value is to 1, the better the model representation. ME is calculated by

$$ME = 1 - \frac{\sum_{i=1}^{n} (x_i - y_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \quad (8)$$

where x is the observed slope gradient value, y is the true slope gradient value, and is the mean gradient value.

In measurements of slope aspect, the index used to compare measured results against the benchmark was the correct group classification. Slope aspect is often classified in 8 groups of 45° each (N, NE, E, SE, S, SW, W, NW). The percentage of correct classification was recorded.

RESULTS AND DISCUSSION

Simulated Test

Comparison of Results for Slope Gradient Calculation

Small differences arose when computing slope gradient using the proposed simplified models. Mean absolute differences in slope gradient estimation bound by ±15° pitch and roll angles were less than 0.12°. The mean absolute difference (MAD) results are shown in Table **3**. Difference in slope gradient estimation between models increases as slope gradient increases as shown in Fig. (**1**). The maximum difference between models occurred when both pitch and roll angles were maximized. The maximum differences obtained between models were: Rowe and Spencer versus Yang - 0.717°; simplified versus Rowe and Spencer - 0.257°; simplified *versus* Yang - 0.460°.

Correlation coefficients between results of different models were greater than 0.999 ($p<0.05$). The error term (ε) introduced with the simplified model can therefore assumed to be negligible for pitch and roll angles up to 15°.

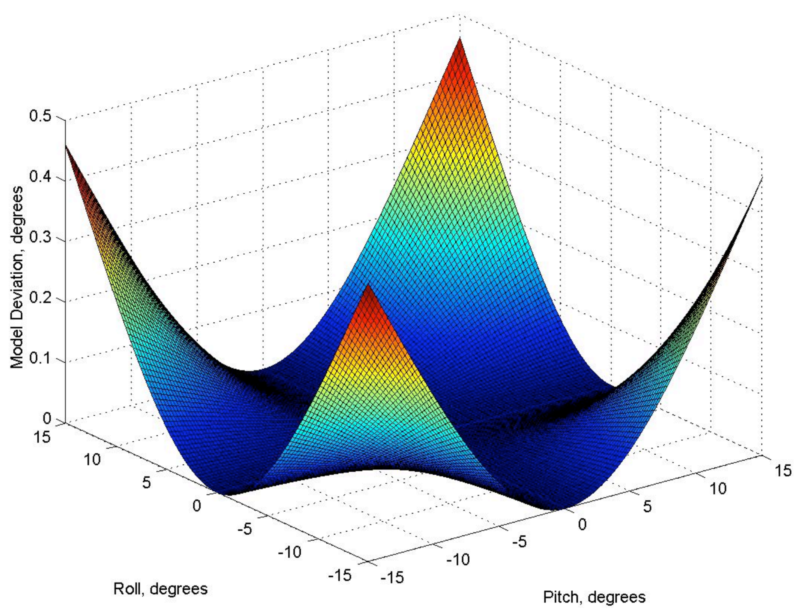

Fig. (1). Surface representing the difference in slope gradient calculation between Yang's model and the simplified model as a function of pitch and roll angles.

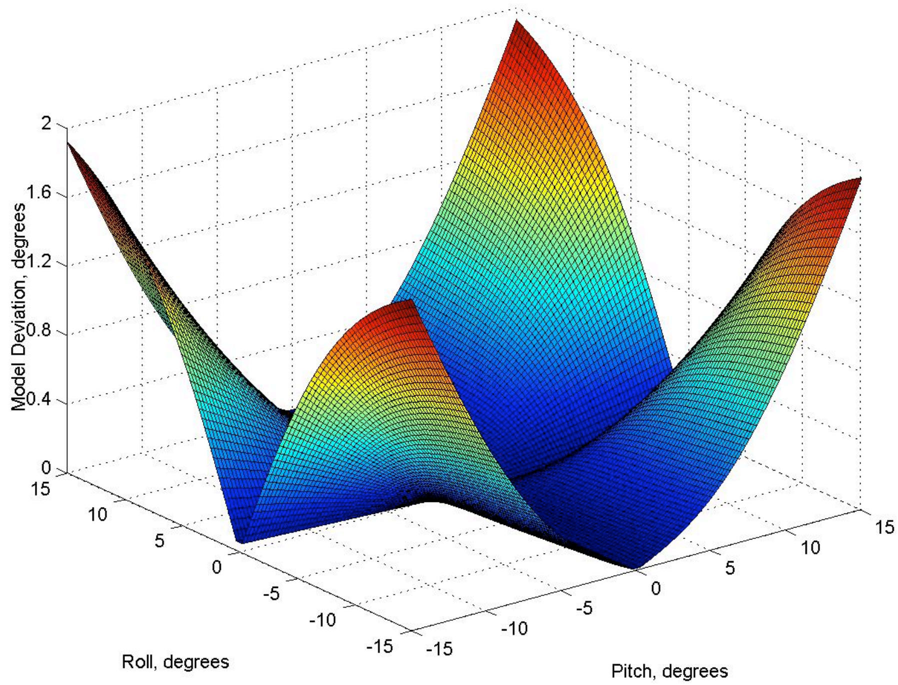

Fig. (2). Surface representing the difference in vehicle attitude between Yang's model and the simplified model as a function of pitch and roll angles.

Table 3. Comparison of Slope Gradient Mean Absolute Deviation between Different Models, in Degrees. Bounded by ±15°

Model	Rowe	Yang	Simplified
Rowe	-	0.113	0.039
Yang	0.113	-	0.074
Simplified	0.039	0.074	-

Comparison of Results for Vehicle Attitude Calculation

The mean differences in vehicle attitude results obtained using different models were less than 0.51°. Complete results are shown in Table **4**. As it occurred with slope gradient calculation, differences were maximized when pitch and roll angles were also maximized. Fig. (**2**) exemplifies the differences found between the simplified and Yang's model. The maximum differences obtained between models were: Rowe and Spencer *versus* Yang – 1.921°; simplified versus Rowe and Spencer - 0.197°; simplified *versus* Yang – 1.921°.

Table 4. Comparison of Vehicle Attitude Mean Absolute Deviation between Different Models, in Degrees. Bounded by ±15°

Model	Rowe	Yang	Simplified
Rowe	-	0.502	0.066
Yang	0.502	-	0.502
Simplified	0.066	0.502	-

Correlation coefficients between results of different models were also greater than 0.999 ($p<0.05$). In vehicle attitude calculations based on pitch and roll angles, the error term introduced with the simplified model can be assumed to be negligible for slope gradient up to 20°.

Field Test Results

Slope Gradient Results

Results of slope gradient estimation using axial measurements of an ATV were compared to the chosen benchmark and showed a high correlation coefficient (r^2 of 0.945), low mean absolute error (MAE = 0.385º) and high model efficiency (ME = 0.931).

Slope Aspect Results

Results showed a percentage of correct classification of slope aspect equal to 85.1%. A chi-square test indicates that there is no significant relationship between errors associated with sensor type or spatial resolution ($\chi 2$ = 0.219, critical value = 0.896).

SUMMARY AND CONCLUSIONS

The objective of this work was to develop simplified models to estimate slope gradient and vehicle attitude based on the measurement of pitch and roll angles of a roving vehicle. The simplification was based on the existing limitation of slope gradient of U.S. cropland. According to the 1997 National Resource Inventory, the majority of cropland in the United States is located on low sloping land, where field slopes usually do not exceed 30%.

Simplified models yield comparable results for both slope gradient and vehicle attitude estimation when compared to published models by Rowe and Spencer [1] and Yang *et al.,* [2] and during field tests. Simplified models have the advantage of being much simpler to be implemented in electronic micro-controllers. During field tests, surfaces computed with slope measurements derived from electronic sensors and compared to highly detailed surfaces yielded a mean absolute error (MAE) of 0.385º and correlation of 0.945. Calculation of slope aspect is also possible buy using vehicle heading and vehicle attitude. A correct classification was achieved 85.4% of the time.

In simulated tests areas where field slopes are less than 15°, differences in slope gradient results using simplified models were less than 0.12°, whereas in vehicle attitude comparisons the differences were less than 0.51°. Correlation coefficients among models' results in both slope gradient and vehicle attitude were 0.999 ($p<0.005$). Simplified models are proved to yield comparable results to published models. The utilization of simplified models reduces the number of mathematical operations improving program simplicity and execution speed.

CONFLICT OF INTEREST

None declared.

ACKNOWLEDGEMENT

None declared.

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