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A New Methodology for Evaluating Guidance Systems for Agricultural Vehicles

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Abstract

Evaluation of new technologies in agricultural machinery guidance is very important and can help producers choose the right equipment for their applications. At present, comparison between different guidance systems has typically been based on the amount of guidance error (i.e., the deviation of the vehicle from the desired path). This paper proposes a new methodology for evaluating these guidance systems. An RTK-GPS was used to record the exact location of a tractor while the operator used one of seven lightbar guidance systems to drive along parallel passes in the field. Frequency-domain analysis of the tractor path was used to compare the performance of the seven systems. Fourier analysis of the tractor path was performed by dividing the changes in the tractor path into low-, medium-, and high-frequency changes. Guidance systems with lower driving error have more high-frequency changes in the tractor path. This means that there is a tradeoff between the driving accuracy and operator workload. It is suggested that a comparison of the frequency spectrum of the tractor path can be used to better evaluate or compare agricultural guidance systems.

Keywords: tractor path, GPS guidance systems, lightbar guidance systems, Fourier analysis.

INTRODUCTION

Guidance of agricultural machinery has received the attention of agricultural engineers since the 1920s. However, in the last few decades, great increases in tractor power, implement size, working speeds, and complexity of operation of agricultural implements have made the operator's task of making steering adjustments (while simultaneously monitoring the implements' performance) much harder (Wilson 2000). Consequently, there is an increasing need for innovative research in this area. Evaluation of new technologies in this area is also of great importance. Typically, evaluation of guidance systems for agricultural vehicles is based on measures of driving accuracy such as average or root-mean-square (RMS) of driving error. Buick and Lange (1998) compared three different guidance systems including a foam marker system and two GPS-based guidance systems based on the amount of overlap. Ehsani et al. (2002) evaluated the accuracy of several Differential GPS (DGPS)-based guidance-aid systems and commented that there is not enough literature published on testing these systems under field conditions. Molin et al. (2002) evaluated the accuracy of a lightbar guidance system under different forward velocities. Ehsani et al. (2004) evaluated a foam marker guidance system based on driving error.

The objective of this study was to develop a new methodology for evaluating and/or comparing different agricultural guidance systems based on the frequency of changes in the tractor path. This represents a human factors approach to the evaluation of guidance systems because the amount of high-frequency and low-frequency changes in the tractor path is closely related to the operator workload.

Fourier analysis was used for frequency-domain study of the path driven by a tractor. Results of the analysis showed a strong relationship between the amount of high-frequency and low-frequency changes in the tractor path with the driving error. The analysis showed that more accurate lightbar guidance systems have more high frequency changes in the tractor path and vice versa. This means more accurate lightbar guidance systems require more steering corrections from the operator and consequently put more workload on the operator. Using this methodology, one can evaluate guidance systems not only based on driving error, but also with regard to the frequency of changes in the tractor path, or equivalently, the workload imposed on the operator.

MATERIALS AND METHODS

Field experiments

The data used in this study were collected in a series of field experiments that aimed at comparing the overall accuracy of the latest versions of seven commercially available lightbar DGPS-based guidance systems while following a straight line (parallel swathing). The lightbar guidance systems used for the experiment included: Cultiva, John Deere, Midtech, Outback, Raven, Satloc, and Trimble. The tests were performed in late summer and early fall of 2001 in an 8-ha (20-acre) wheat field in central Ohio. Several measures were taken to ensure a fair comparison: all the guidance systems were tested on the same day, the order of the guidance systems for each day was randomly selected, the same driver and tractor (John Deere 4640) were used for all tests, and the swath width was constant at 12.2 m (40 ft) in all experiments. The latest available versions of firmware were installed in all guidance systems and all system configurations and settings were based on the manufacturers' recommendations. To determine the exact location of the tractor in the field, a Real Time Kinematic (RTK) GPS was used (Trimble 4800 for rover unit and Trimble 4600 for base station) (Ehsani et al. 2002).

Analysis of data

Figure 1 shows a sample of the data showing the exact position of the tractor in State Plane Coordinate System (abbreviated as SPCS). Line A-B is the first pass, after which the driver made nine parallel passes using a lightbar guidance system. For each pass, we first found the regression line for the data points. Then, we calculated the vertical distance between data points and the regression line; this distance is the deviation from the desired straight path the tractor should have followed and is hereafter referred to as "driving error". Finally, we plotted the driving error values against the position of the tractor along the path. After that, spline curve fitting was performed using a single spline for the entire length of each pass. Data analysis was performed using Matlab (Mathworks Inc.).

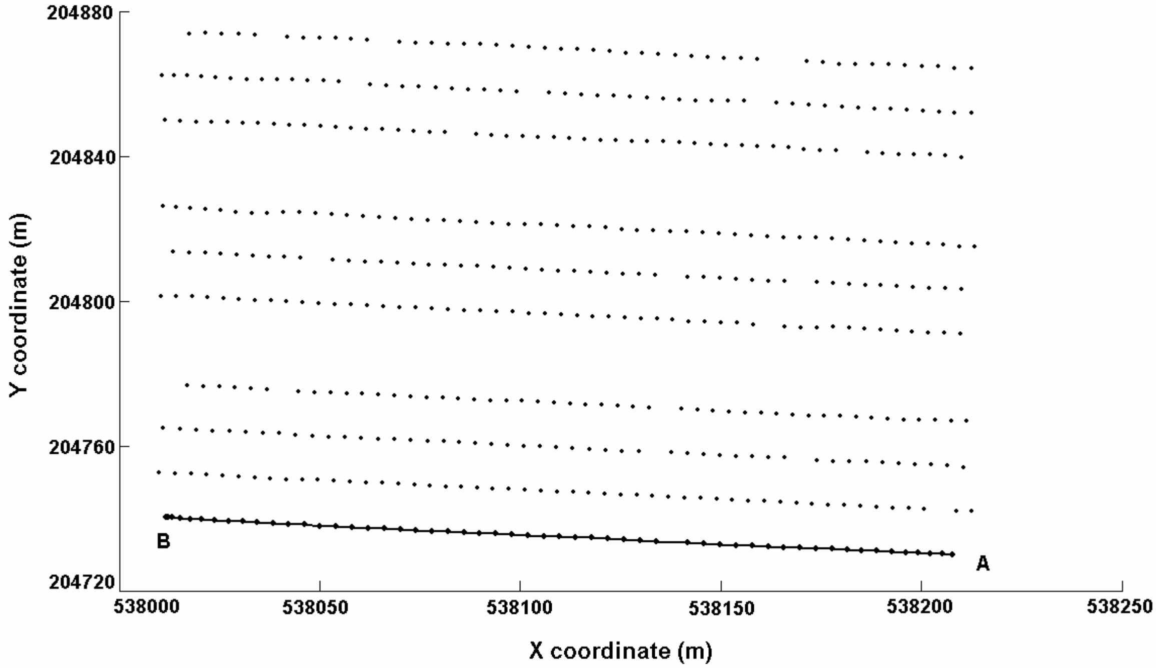

Fig. 1. An example of driving path data provided by RTK-DGPS measurement of tractor location.

Fourier analysis

Fourier transform of the best-fit spline was obtained using the following equation (Oppenheim et al. 1997):

$$Y(j\omega)=\int_{-\infty}^{+\infty} y(x)e^{-j\omega x}\,dx \tag{1}$$

where:

x = distance along the path

$y(x)$ = driving error at position x

$Y(j\omega)$ = value of Fourier transform for frequency equal to ω

ω = frequency, here ω is 'positional frequency'; since x is distance (m), and since the outcome of the multiplication ω•x needs to be dimensionless, therefore the dimension of ω is 1/distance (i.e., L^{-1}).

RESULTS AND DISCUSSION

Spline curve fitting

For each tractor pass, spline curve fittings were carried out using a single spline of 5th degree. Starting with a 30-piece spline, the number of pieces was incremented until there was no apparent improvement between two successive fits. Such a spline would always pass through all data points, theoretically eliminating fitting error. An example is shown in Figure 2.

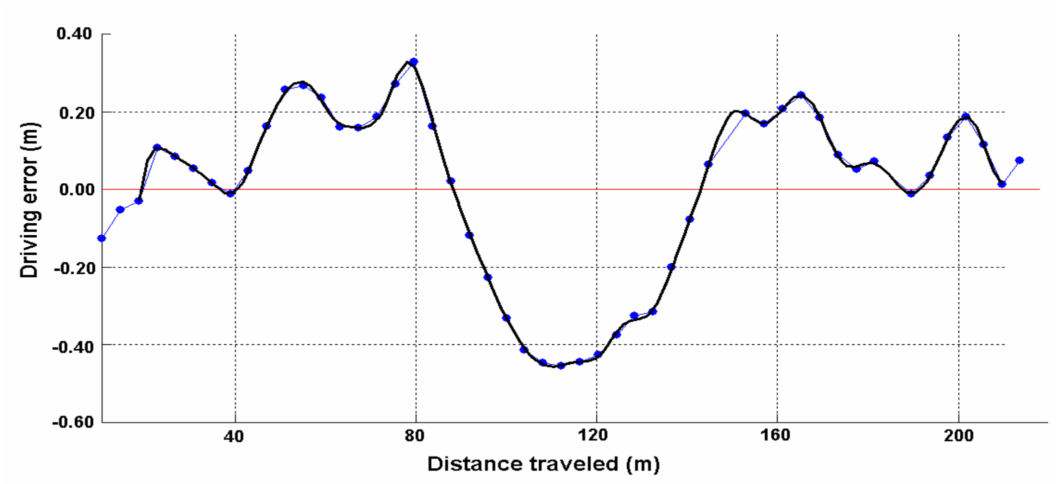

Fig. 2. A sample plot of driving error values (small solid circles) and spline curve fitted to these points.

Fourier analysis

Fourier analysis of the driving error data was performed using continuous-time Fourier transform of the best-fit spline (using Eq. 1). An example of the resulting spectrum is shown in Figure 3. The horizontal axis represents ω in Fourier transform analysis formula (Eq. 1). To make sense, it can be related to the period, using the following equation:

$$T = \frac{2\pi}{\omega} \qquad (2)$$

As mentioned previously, ω is in units of m^{-1} and T (period) is in units of m. For example, the graph shows that in this case the strongest harmonic has a frequency of approximately 0.087 which corresponds to T=72m. This represents a sinusoidal path as seen in Figure 4.

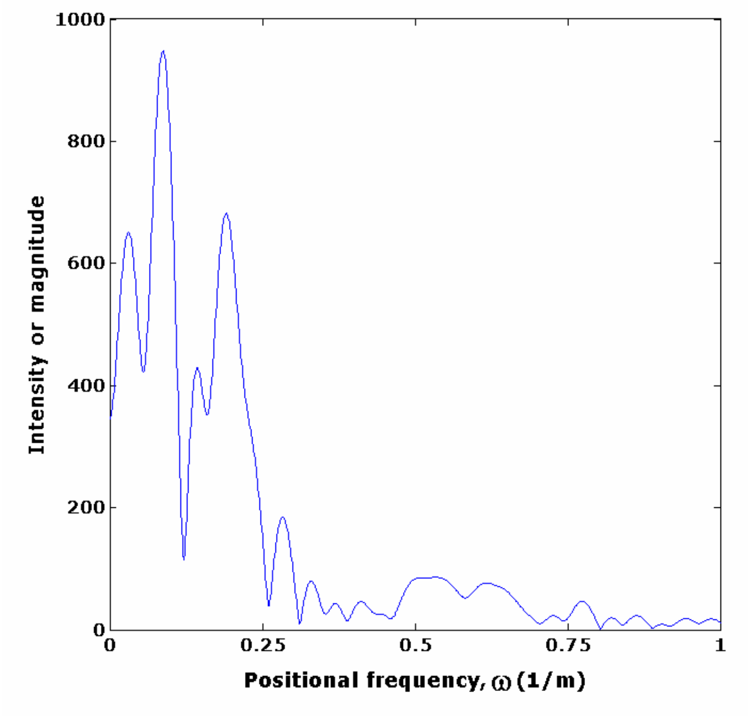

Fig. 3. An example of Fourier transform magnitude plot.

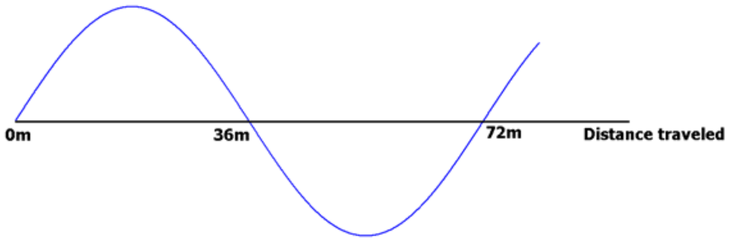

Fig. 4. Sinusoidal path corresponding to an ω = 0.087 in Fourier transform plot.

Therefore, T is twice the distance traveled during each excursion for the specific harmonic. We divided the entire spectrum into four parts:

ω = 0 to 0.126 which corresponds to changes (harmonics) with T > 50 m
ω = 0.126 to 0.251 corresponding to changes with 50 m > T > 25 m
ω = 0.251 to 0.628 corresponding to changes with 25 m > T > 10 m
ω = > 0.628 corresponding to changes with T < 10 m

For each pass, we calculated the amount of energy in each of the four parts of the spectrum using the following formula (Oppenheim 1997).

$$E = \int \left| X(j\omega) \right|^2 d\omega \tag{3}$$

Then we divided the energy in each part by the total energy of the spectrum to obtain the fraction of energy (in percent) for each of the four parts of the spectrum. The RTK GPS data showed the exact location of the tractor every 4-5 m along the path. Based on Nyquist criteria, the analysis was not theoretically able to detect changes with a period of less than 8-10 m. Therefore, the last part of the spectrum (corresponding to $T < 10$ m) was ignored. For further analysis, the remaining three parts were considered (please see Fig. 5):

Low frequency changes: changes with $T > 50$ m,
Medium frequency changes: changes with $50 \text{ m} > T > 25$ m,
High frequency changes: changes with $25 \text{ m} > T > 10$ m.

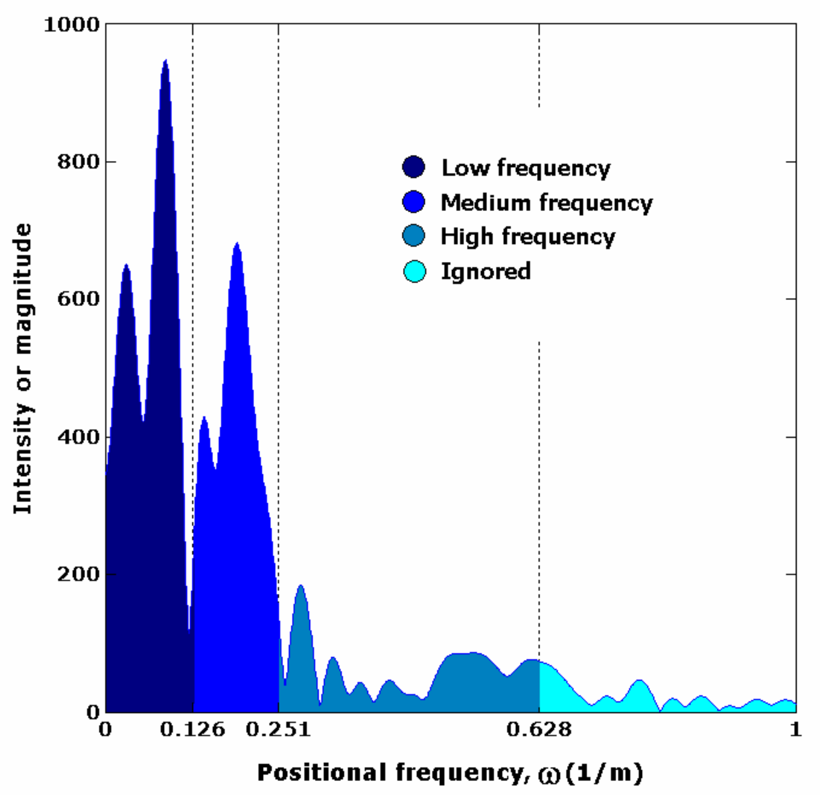

Fig. 5. Partitioning of frequency spectrum.

Analysis of variance was used to compare the seven different GPS systems. Using SAS software, a Tukey's test (with α=0.05) was used to compare the different systems. The following table shows a summary of the results with different superscripts (within the same column) indicating significantly different means.

Table 1. Comparison of root mean square driving error (cm), amount of energy in low-frequency portion of the spectrum (percent), and amount of energy in high-frequency portion of the spectrum (percent) between different lightbar guidance systems.

Guidance System	RMS Driving Error (cm)	Energy in low-frequency portion of spectrum (%)	Energy in high-frequency portion of spectrum (%)
Outback	11.1[a]	38[b,c]	24[a]
John Deere	11.1[a]	31[a,b]	27[a]
Raven	12.6[a,b]	33[a,b]	26[a]
Satloc	14.3[a,b,c]	28[a]	28[a]
Cultiva	17.0[b,c]	45[c,d]	19[b]
Trimble	18.2[c]	47[d]	18[b]
Midtech	18.6[c]	48[d]	19[b]

The general trend revealed by the above analyses can be stated briefly as "systems with lower error have more high-frequency changes and less low-frequency changes in the tractor path." This fact can be more clearly depicted by plotting the values of RMS of driving error versus the amount of low-frequency and high-frequency changes in the path as shown by the following graphs.

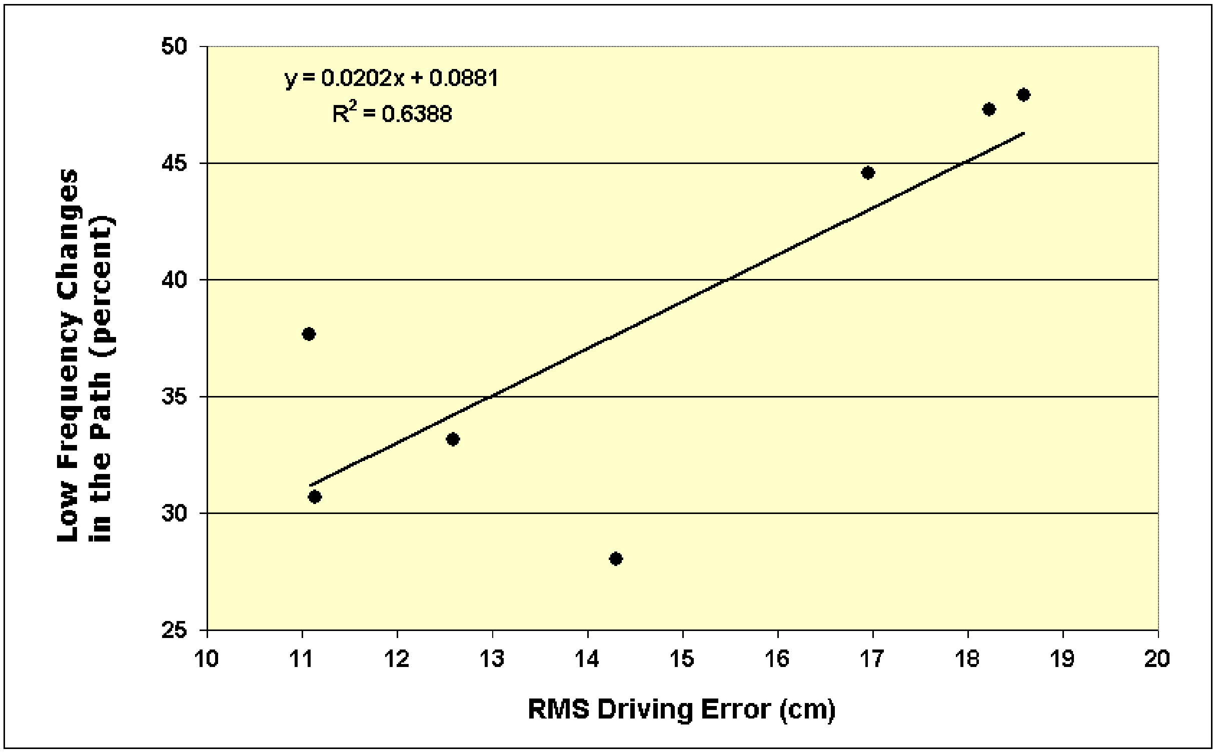

Fig. 6. Relationship between driving error and amount (percent) of low-frequency changes in tractor path. Each circle on the graph represents the average for one of the seven guidance systems compared.

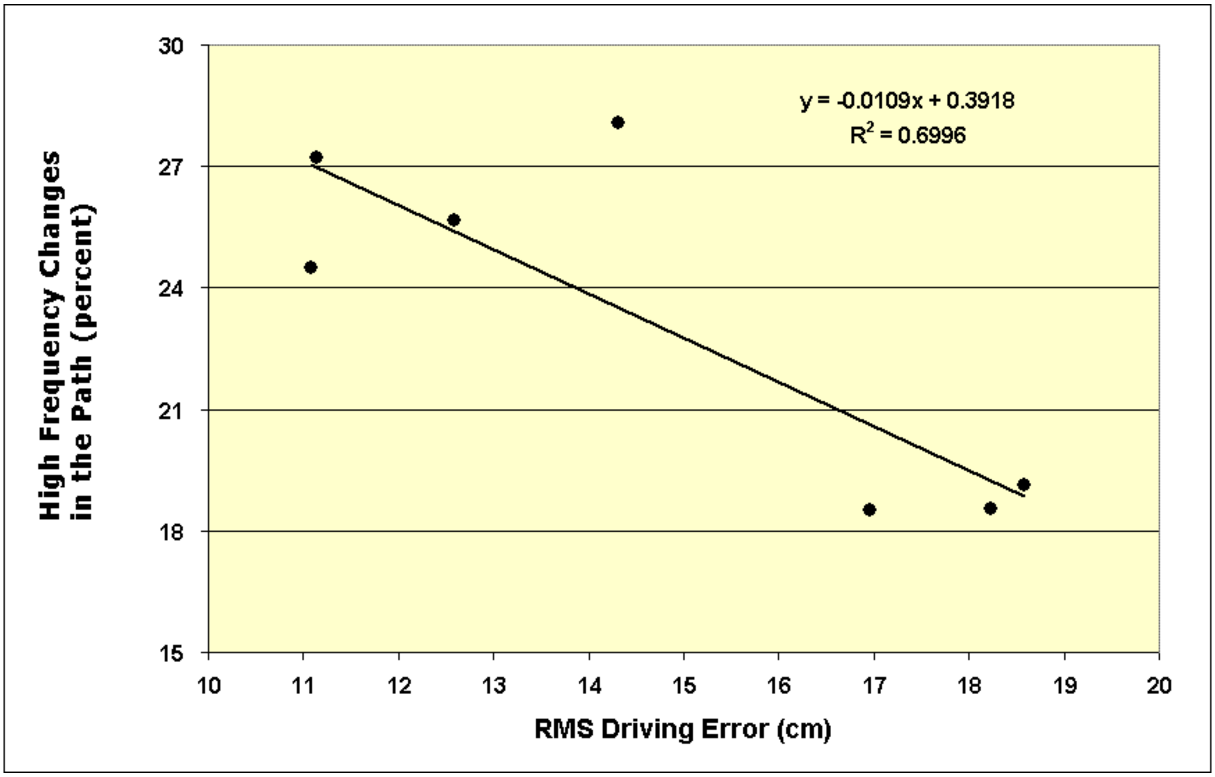

Fig. 7. Relationship between driving error and amount (percent) of high-frequency changes in tractor path. Each circle on the graph represents the average for one of the seven guidance systems compared.

These results show a strong relationship between the driving error and the frequency of changes in the driving path. The main conclusion is that lightbar guidance systems with lower error in parallel swathing have more high frequency changes in the path of the tractor. From the operator's point of view, this translates into more steering adjustments requested by the guidance system (through the lightbar).

CONCLUSIONS

The objective of this study was to develop a methodology for evaluating or comparing different guidance systems for agricultural vehicles. Field experiments were performed with the tractor operator with the goal of driving along parallel straight passes using each of seven lightbar guidance systems. We used spline curve fitting to approximate the tractor's actual path in the field. Fourier analysis of the tractor path was performed to find the frequency of changes in the path. Comparison of results for different guidance systems showed a strong relationship between the frequency of changes in the driving path and the driving error: guidance systems which yielded more accurate driving (less driving error) showed more high-frequency changes in the tractor path. This means that more accurate lightbar guidance systems come with the cost of more workload on the operator (i.e. more accurate systems require more steering adjustments of the driver).

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