MODELING OF STRAIGHT-LINE DRIVING WITH A GUIDANCE AID FOR A TRACTOR-DRIVING SIMULATOR

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ABSTRACT. *Minor steering corrections are necessary to keep a tractor moving in a straight line. If the factors that cause such steering corrections are not considered in the implementation of a driving simulator, the task of straight-line driving will be both unrealistic and too simple. The objective of this study was to develop and validate a model, for simulation of parallel swathing in a tractor-driving simulator, which accounts for both guidance system error and tractor self-deviation. Guidance system error and tractor self-deviation were both measured by an RTK GPS system. Fourier analysis was used to determine the energy spectrum in high-, medium-, and low-frequency regions. Complex sinusoids which had similar energy distributions to those obtained from field measurements were proposed for both guidance system error and tractor self-deviation. To validate the straight-line driving model, root mean square (RMS) and frequency composition of lateral deviation of the vehicle were determined for both the tractor-driving simulator and several real systems consisting of a tractor, driver, and lightbar guidance device. Six subjects participated in the simulator study. On average, the RMS of lateral deviation was 33 cm. The energy distribution was 32% in the high-frequency region, 39% in the medium-frequency region, and 29% in the low-frequency region. Field experiments with a single driver with seven distinct lightbar guidance systems yielded an average RMS of lateral deviation of 15 cm. The energy distribution was 27% in the high-frequency region, 41% in the medium-frequency region, and 32% in the low-frequency region. Field experiments with seven drivers using a single lightbar guidance device yielded an average RMS of lateral deviation of 30 cm. The energy distribution was 30% in the high-frequency region, 40% in the medium-frequency region, and 30% in the low-frequency region. Field experiments showed close agreement with simulator experiments in terms of the frequency composition of the lateral deviations.*

Keywords. *Parallel swathing, Straight-line driving, Tractor lateral deviations, Tractor-driving simulator, Lightbar guidance system.*

Driving simulators date back to the 1970s when General Motors developed one of the first driving simulators (Gruening et al., 1998). Today, driving simulators are being used as effective research tools in several areas including vehicle system development and human factors studies. They enable researchers to reproduce real driving situations in a safe and easily controllable environment (Lee et al., 1998). Rapid increases in the computational power and graphic capabilities of desktop computers over the last decade have enabled researchers to build high fidelity driving simulators at reasonably low cost. Although driving simulators have been extensively used in the automotive industry for many years, only a small number of driving simulators have been developed for agricultural vehicles; the work by Wilkerson et al. (1993) is one of the few examples.

Most field operations are performed in parallel swathing mode which consists of driving the agricultural vehicle along a series of parallel paths to cover the entire field. Although the desired path might be a straight line, the driver has to constantly make steering adjustments to keep the tractor on target due to unevenness of the field surface and imperfections in both the vehicle and the guidance system. A good tractor-driving simulator must provide a realistic replication of straight-line driving. For straight-line driving on a simulator to be realistic, the simulator must account for the factors that contribute to deviations of the tractor from the desired straight line. The nature of these factors must be described in mathematical terms.

In some ways, automobiles are similar to tractors because imperfections that contribute to lateral deviations exist in both systems. Standard Deviation of Lateral Lane Deviations (SDLLD) has been used to compare the performance of automobile-driving simulators to actual automobile driving (Allen et al., 1994). It is common for SDLLD to be smaller for simulator driving than for automobile driving, possibly because automobile-driving simulators do not consider the minor imperfections that exist in real driving conditions (Green, 2005). To prevent this problem, Green (2005) suggested introducing some disturbance to cause the simulated vehicle to deviate from the straight path.

Despite the similarities between a tractor and an automobile, the nature of disturbances is quite different due to different driving surfaces and forward speeds. Furthermore, tractor operators often use a guidance system to achieve higher straight-line driving accuracy. The interaction

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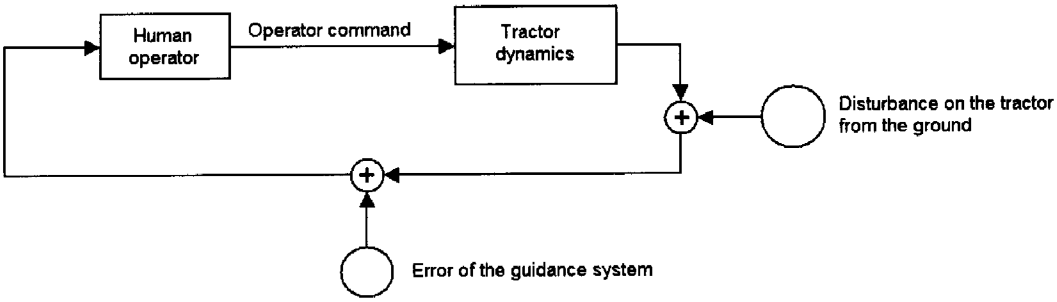

Figure 1. Block diagram representation of driving in parallel swathing mode.

between the driver, the tractor, and the guidance system in straight-line driving can be illustrated by a simplified block diagram (fig. 1). Motion of the tractor is a superposition of the movements due to steering commands and the disturbance from the ground surface. The guidance system has its own error. Proper simulation of the straight line driving requires an understanding of both the disturbances on the vehicle and the guidance system error.

The objective of this study was to develop and validate a model for simulation of parallel swathing in a tractor-driving simulator that accounts for both guidance system error and tractor self-deviation.

PROCEDURE FOR MODEL DEVELOPMENT AND VALIDATION

The first step in developing the straight-line driving model was to determine mathematical descriptions of guidance system error and tractor self-deviation. After modifying the code of the tractor-driving simulator, experiments were completed with the simulator. Root mean square (RMS) and frequency composition of lateral deviation of the vehicle were determined. Field experiments were also completed using tractors driven through agricultural fields in response to guidance information provided by lightbar navigation devices. Root mean square (RMS) and frequency composition of lateral deviation of the vehicle were determined. Comparison of the data obtained with actual vehicles to the data obtained with the tractor-driving simulator was used to determine the validity of the straight-line driving model.

DATA ANALYSIS PROCEDURES

The raw data collected in this study were position data of either the real vehicle or the simulated vehicle. These position data were analyzed by first calculating the deviation from the desired straight line (i.e., cross track error) for each pass. Then, Fourier analysis was performed to obtain the frequency composition of these deviations. Discrete Fourier analysis requires data points to be equally-spaced. Because this was not the case for the data, a spline curve was first fitted to the data points. The number of pieces of the spline was increased until the spline passed through all data points, eliminating fitting error. Figure 2 shows an example of the error data and the fitted spline curve.

Next, a continuous-time Fourier transform was applied to the spline curve $y(x)$ (Oppenheim et al., 1997):

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

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), the dimension of ω is 1/distance (i.e., L^{-1}).

An example of the resulting spectrum is shown in figure 3.

The horizontal axis is in the period, T, instead of the frequency, ω, because it is easier to interpret. In fact, T is twice the distance traveled during each excursion for the specific harmonic. T is in units of m and is related to ω through the following equation:

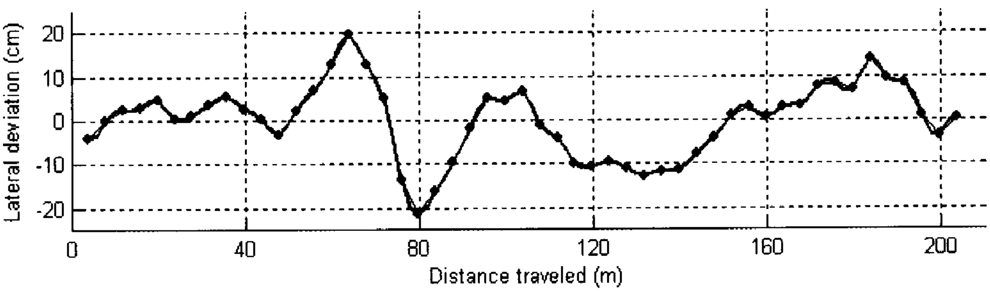

Figure 2. A sample plot of the error of the lightbar guidance system (small solid circles) and a spline curve fitted to these points.

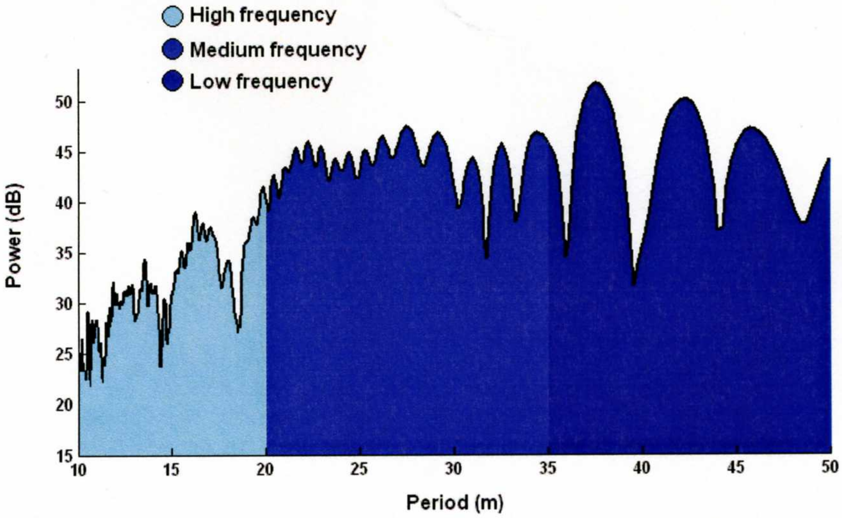

Figure 3. A sample spectrum of the error of the guidance system.

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

The spectrum was divided into three parts:

- T = 10 to 20 m, the high-frequency region
- T = 20 to 35 m, the medium-frequency region
- T = 35 to 50 m, the low-frequency region

Because data were recorded at 4- to 5-m intervals along the path, the computation of the spectrum for periods smaller than 10 m was not possible based on the Nyquist criterion. Also, because of limited length of each pass (less than 200 m in most cases), computation of the frequency spectrum was not valid for periods larger than 50 m. These are the reasons for choosing the frequency ranges.

The energy of the power spectrum for the range of frequencies ω_1 to ω_2 can be computed using the following equation:

$$energy = \frac{1}{2\pi}\int_{\omega_1}^{\omega_2} \left|Y(j\omega)\right|^2 d\omega \qquad (3)$$

For each pass, energy of the spectrum in each of the three regions was computed. Then, the energy in each of the three regions was divided by the total energy in the spectrum to obtain the normalized values (in percentage) for each of the three regions.

ERROR OF A LIGHTBAR GUIDANCE SYSTEM

This experiment was performed to evaluate the error of a lightbar guidance system. Although this error will be dependent upon the specific characteristics of the lightbar guidance device, a thorough characterization of the error of all lightbar guidance devices is beyond the scope of this research. The decision was made to investigate the error of one commercial system - the Outback S® (Hemisphere GPS, Calgary, Alberta, Canada) - because of its availability.

This experiment was performed in a parking lot on the campus of the University of Manitoba, Canada; a Leica GPS1200 RTK (Leica Geosystems, St. Gallen, Switzerland) system was used to provide accurate measurements. The antenna of the lightbar guidance system was placed close to the RTK GPS antenna on a small, four-wheeled cart. The lightbar was also placed on the cart. Parallel-swathing runs were performed by manually guiding the cart according to the lightbar signal. Because the cart was easily maneuverable and tests were performed at low speed (approximately 0.3 m/s), it was possible to achieve zero error on the lightbar for most of the duration of the test. When the error shown on the lightbar was not zero, data logging was stopped until the lightbar error was re-zeroed (i.e., by adjusting the position of the cart). Consequently, the experiment produced a set of RTK data points showing the trajectory of the lightbar antenna when the lightbar indicated no lateral error.

The root mean square (RMS) of error of the lightbar system was approximately 14 cm. Fourier analysis showed that, on average, 23% of energy of the spectrum was in the high-frequency region, 38% in the medium frequency region, and 36% in the low-frequency region of the spectrum. The mathematical function to be added to the tractor-driving simulator to represent guidance system error (fig. 1) should have similar characteristics.

The literature on human tracking control suggests that a sum of three or more sinusoids with different frequencies is perceived as random to human operators (Jagacinski and Flach, 2002). Therefore, it is sufficient for this function to be a summation of three or more sinusoids. The third condition is that the RMS of the function values should be approximately 14 cm. The following mathematical function, for example, satisfies these three requirements.

$$y(x) = 9.6\sin(0.42x) + 12.3\sin(0.25x) + 12\sin(0.16x) \qquad (4)$$

where

$y(x)$ = the cross-track error of the lightbar guidance system (cm)

x = distance traveled (m).

DISTURBANCE DUE TO TRACTOR SELF-DEVIATION

This experiment was conducted to develop an insight into the nature of the disturbance on a tractor moving in a straight line. Once again, a comprehensive examination of this phenomenon is beyond the scope of this study. Rather, the goal was to gain some general knowledge about this phenomenon by studying a specific case. Therefore, only one