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Research

Magnetic Lateral Indication System Evaluation

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MAGNETIC LATERAL INDICATION SYSTEM EVALUATION

Final Report

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Introduction:

In the following we present a brief summary and analysis of the 3M report entitled "*Magnetic Lateral Indication System for Vehicles: Mn/ROAD Demonstration*" prepared under Mn/DOT Agreement No.: 73646-P with 3M. We only received the report on Dec. 11, 1996. Our contract was extended to Dec. 31, 1996 (from the original term of March 1, 1996 to Sept. 30, 1996) in order to complete this analysis. An earlier draft delivered on Sept. 21, 1996 was inadequate for basing any conclusions.

This report summarizes our conclusions and recommendations regarding the Magnetic Lateral Indication System. It analyzes the results and conclusions that were derived by 3M and Honeywell.

We are working on two other related documents. This work discussed in these two reports represent effort also supported under Mn/DOT Agreement no. 74708, University of Minnesota TOC #2, entitled: "SAFETRUCK - Sensing and Control to Enhance Vehicle Safety."

The first of these (titled "Human Centered Vehicle Control Systems") discusses the sensory and preview requirements that humans need to safely drive a vehicle manually. This is then compared to the requirements placed on an autonomous driving system. This analysis (part of our original workplan) represents a synthesis of the literature on the subject and makes specific conclusions regarding the requirements imposed on any lateral indication systems and the information presented to the driver, especially with regard to preview. Given the nature of a magnetic tape, it is not unreasonable to encode preview information into such a tape, but recommendations are needed vis a vis how much preview (in terms of time or distance) and the nature of this preview. This report is general in nature and its conclusions apply to other sensing approaches as well as to the magnetic tape and magnetometer based approach.

The second of the two related reports (titled: "Real Time Position Sensing for Highway Vehicles: Evaluation of Differential GPS") documents the methodology (and results) for measuring the performance of a lateral indication system. This report was prepared in order to describe one approach that may be used to document the specifications of the magnetic lateral indication system when it is ready for further tests. Although the method is described in terms of measuring the performance of a DGPS based system, the technique applies as well to the evaluation of a magnetic tape based approach. We felt that the methods used and described in the 3M report for evaluating the performance of the magnetic system were inadequate (or at least inadequately documented). This second report remedies the situation. This report will be issued after NovAtel has had a chance to review the results and comment on our approach.

Evaluation of the 3M Report

Overview:

The final report entitled "*Magnetic Lateral Indication System for Vehicles: Mn/ROAD Demonstration*" provided by 3M (including experiments and an analysis developed and provided by Honeywell) represents a feasibility study of a lateral position indication system for vehicles. Although this system is primarily designed for measuring lateral displacements, it is also described as being able to measure longitudinal displacements. *We understand that this study was performed at early stages of the development of the magnetic lateral position indication system. As such, one ought to consider our comments regarding the study in that context.*

The Magnetic Sensing Concept:

The concept on which the development of this sensor system is based on the following: A pavement marking tape is applied to the road and is permanently magnetized so that it produces a magnetic field which alternates between a north and south magnetization, at fixed distances along the length of the tape. The distance between a N-S pair was 7 feet in this study. The selection of a distance other than 7 feet is also possible. This approach was used in order to allow the sensors to distinguish the tape's weak magnetic field from the Earth's magnetic field and was chosen so that interaction with other potential magnetic field sources is minimized. In addition to the magnetized tape, a magnetometer which contains three magneto-resistive elements oriented in orthogonal directions is mounted on the vehicle. This sensor produces three signals (along three perpendicular directions) which are related to the strength of the magnetic field around the tape, and is a function of the position and orientation of the magnetometer on the vehicle. Finally, an algorithm was devised which generates an estimate of the lateral position from the magneto-resistive sensor to the magnetic tape based on the three measurements of the magnetic field provided by the magneto-resistive elements.

Lateral displacements produced by the magnetic system were compared against measurements made independently by an optical system (a camera consisting of a one dimensional CCD array) mounted on the vehicle at a height of 5 feet.

Experiments:

Initial field measurements were taken at a road located at the 3M Traffic Control Materials Division's Transportation Safety Center in Cottage Grove. A three-wheeled cart which carried the sensor module and a computer was used in these first experiments. This cart which was constructed out of non-magnetic materials was pushed along at a walking pace of about 6 feet/sec. Data was collected at 2-inch intervals with the magnetometer mounted at a height of 12 inches from the ground. It is important to note that in these experiments a magnetic tape of varying width and wavelength was used.

A second set of experiments was performed at the Mn/ROAD track on different days. In these experiments, the camera was placed at a measured lateral offset to the magnetometer mounted on a vehicle. The vehicle was then driven so that the camera was approximately over the tape and intentionally deviated about 1 foot on either side of the tape.

Mathematical Models:

From the initial field experiments at Cottage Grove, a magnetic pole model of the field surrounding the tape was developed. The model predictions of the strength of the magnetic field along the three orthogonal directions were compared to the amplitude components of the Fourier series of the signals measured by the magnetometer, corresponding to the same frequency as that of the tape's wavelength. This was done in order to evaluate how good the model was at predicting the sensor's behavior and was needed in order to evaluate how good an understanding one had of the underlying mechanisms of the sensor's behavior. The model predictions were found to be in reasonably good agreement with the data.

Algorithms:

3M devised a computational algorithm to compute lateral displacements from the three magnetic field components. A separate algorithm then filtered the field components due to the tape from the noise. It was found that in addition to the amplitude measurements, the phase information of the magnetic field components were also required, in order to be able to use the sensor to measure (estimate/predict) lateral displacements on both sides of the tape. The approach

requires that the magnetometer pass over several periods of N-S wavelength, i.e. multiples of 7 ft., in order to calculate a lateral offset. This results in a time lag (which is a function of vehicle speed). The more wavelengths covered, the better the estimate (i.e. the better the system is able to eliminate extraneous signal noise and thus the better the filtering efficiency), but the longer the time lag. There is clearly a tradeoff between filtering efficiency and the time lag associated with the lateral displacement estimates produced by the algorithm. The smaller the time lag (less number of wavelengths used to compute the lateral displacement), the more extraneous noise that remains in the results, i.e. the worse the impact of other factors. As a practical compromise, 3M chose to estimate lateral offsets based on two wavelengths (i.e. each wavelength is 2 x 7 or 14 ft.; two wavelengths are therefore 28 ft.). This means that at 30 mph, a result is not available until 0.63 seconds after the actual measurement, at 40 mph, a result is not available until 0.47 seconds after the actual measurement, and at 60 mph, a result is not available until 0.32 seconds after the actual measurement.

It is interesting to note that lateral distance calculations were not made in real time since the algorithms were not available at the time the experiments were performed. Also, Honeywell devised a separate set of algorithms that operated on the raw data in the reverse order of the 3M algorithms, i.e. the Honeywell algorithms first filtered the data and then computed the lateral distance measures as compared to the 3M algorithm which first computed the lateral distance measures from the magnetic field measurements and then filtered out the components due only to the magnetometer. Honeywell admits that the Fourier series techniques used by 3M are superior, but may be more computationally “expensive” (pg. 30).

The Optical Reference System:

The development of the magnetic pole model and the algorithm for determining the lateral distance from the tape was followed by a comparison of the post-processed lateral displacement data against a reference measurement (i.e. a ‘ground truth’), which as we mentioned earlier, was made using an optical sensor based on a CCD camera. The camera was calibrated only once, when the vehicle carrying the camera was stationary. Appendix A (operational test plan) specifies that the ground truth sensor should have an accuracy and repeatability of 0.25 inches, however the report does not document how this was achieved using this optical system.

Critical Comments:

Conclusions discussed in the Final Report (Chapter 5):

The figures documented in the text of the report that we examined (most of the significant test and error results are contained in Chapter 4.2.5) imply that the system exhibited reasonable performance only up to about 15 inches of lateral offset. We don’t feel that the results presented in the body of the report justify any strong conclusions about the utility of the measurements at two or higher feet. For example, the numbers presented in the first paragraph of Chapter 5 indicates that there are three inches of error at lateral offsets of 2 feet (12.5 % error). This is not necessarily a “good” result (obviously dependent on the system’s application), *especially if the magnetic stripe runs along the lane boundaries and not down the lane center*. For this sensor, the standard deviations grow significantly with lateral offset. As a result of this characteristic of the sensor, its final application must be carefully considered. Figure 25 implies that the results beyond 15 inch offsets are not very good (due to high standard deviations). The mean error offsets shown in Figure 26 indicate that the best results are between 2 and 14 inch offsets, but no explanation is given for the mean error offsets getting larger for lateral distances under 2 inches.

In fact, Honeywell (in section 4.2.6) indicates that using simple algorithms, “24 inches appears to represent the maximum feasible range.”

There is also no discussion of the vehicle speeds at which the data was collected. Were the errors a function of vehicle speed? How was the latency (associated with the computational speed of the algorithm) or the lag handled in computing the errors?

We agree with the conclusion that “the performance demonstrated in this study would certainly be sufficient to inform a driver when the vehicle entered a zone three or four feet from the edge, although the location would be known only to within six inches or so.”

We agree with the report’s conclusions that the system exhibited inadequate performance for closed loop vehicle guidance (in outdoor applications) unless significant design changes are made.

Abstract of the Final Report:

We feel that the comment in paragraph 3 of the abstract, “Reliable estimates of position were obtained for lateral displacements up to about three feet” should read “up to eighteen inches” or at best “up to two feet.” There is no justification in this report for any conclusions beyond two feet offsets.

Sensor Characteristics:

Linearity: The magnetic sensing system is clearly non-linear in behavior. The report implies that the non-linearities can be removed because they are consistent, however the figures presented don’t seem to back this up. (Figure 17: “good results” only up to 12 inches.)

Noise: Apparently there seems to be considerable magnetic noise at the MnROAD site, but its effect on the final results (i.e. lateral position errors) is not clear.

Accuracy: Accuracy has been specified to be less than 1 inch, however this is suspect given that dynamic tests were not performed on the optical system’s accuracy.

Bandwidth: No specific comments have been made regarding the bandwidth of the magnetic sensing system.

Lag time: The sensor output will always lag behind the true instantaneous vehicle position . In the present configuration, the time required to traverse 2 cycles of magnetic wavelength (28 ft.) will be dependent on vehicle speed. This will affect how the sensor can be used.

Data/Computational Latency: No specifications are given on the time required for algorithmic computations and final data availability. No results are presented for the effect of vehicle speed on the error.

Detailed Comments on the Report:

- Section 3.1, Figure 5: Abscissa, units, tape width not specified.
- Significance of Table 2 is not clear.
- Figures 9 through 11 imply good fit for the magnetic model for 13 inches and 25 inches from the tape but there are problems at closer distances from the tape and distances above 35 inches. We do not understand why the results at 1 inch distance are much worse than those at 13 and 25 inches.
- Section 3.2: In the Honeywell computational algorithm, the substance of the final (best) algorithm is not clear. It is not clear whether the model was used or not. It is implied that a “relatively simple sign algorithm” was used, however its significance is not explained.

- Honeywell only documents an analysis of the magnetometer magnetic field model and errors in the model. It does not discuss or analyze the final lateral position sensor errors.
- No significant conclusions are evident from the following sections: Measuring Longitudinal Distance (3.2.4), Error Models (3.2.5), Response (3.3). It is not clear how these sections tie in to the rest of the report.
 - Section 4: The logical reasoning provided in 4.2.1 is not entirely clear. From four data points (Figures 16, 17) one cannot draw conclusions. Sections 4.2.1 to 4.2.4 contain many figures and tables that don't mean anything. *It is Section 4.2.5 that provides the most significant experimental results.*
 - Figures 18, 19: Significance is not clear. Proper legends on the graph absent.
 - Page 25: A correction was used in the 3M's position algorithm. "The position calculated actually represents an estimate of where the vehicle was one cycle (14 ft.) back. Therefore the camera's longitudinal distance was adjusted to remove this difference" - we are assuming the authors meant that a 14 ft. offset was "removed" from the results documented in 4.2.5. This means that the magnetic based measurement system provides lateral position estimates that occurred 14 ft back from the vehicle's instantaneous position. Are the experimental results based on the last 28 ft. (2 cycles) of data or 14 ft. of data? There is no discussion of the significance of this on the ultimate application of the system.
 - Figures 20, 21: Results at time $t=0$ are not shown. Why?
 - Figures 23 - 26: Results imply that one can only predict lateral deviations up to about 1 foot (maybe 15 inches).
 - Figure 27: Significance is not clear.

Conclusions:

In conclusion, we feel that the most significant issue related to the sensor's design and performance is its time lag (and latency). The effect of this time lag on the potential application of the system is not discussed in the 3M report. For example, there has been considerable discussion in the human factors literature, regarding the problems that humans have with a time lag/latency in the control loop. The report that we have prepared ("Design of Human Centered Vehicle Control Systems") has focused on the issue of preview (see recommendation below) and not on the problem of a delay in the sensory feedback. A brief discussion that we recently had with human factors experts indicate that depending on many factors that cannot be summarized here, problems may occur at sensor feedback time delays of about a third of a second, exactly the lag that appears in this sensor at 60 mph. Longer delays may be worse. If 3M is considering the use of the sensor in steering buses in narrow lanes; this comment should raise a red flag that this issue must be thoroughly investigated before proceeding. We feel that this is the most troubling disadvantage of the sensor in its present configuration.

We agree with the 3M report that more work is needed. It is evident that independent yaw and velocity measurements will be required in most applications, unless there are significant changes incorporated into the system design. Finally, although the results from this first study shows promise for some applications, we feel that a careful re-examination of the sensing system's design is warranted. More specific recommendations are made in the next section.

Recommendations:

Experimental Procedures:

We feel that the experimental design for evaluating the accuracy of the magnetic lateral position measuring system was less than optimal. We do not feel that the optical sensor used as a ground truth was sufficiently tested (i.e. to verify that it meets the original .25 inch accuracy specification). The dynamic effects of vehicle and road dynamics on the magnetic and camera

measurements were not taken into consideration. As is mentioned in the report, there exist *systematic differences between the position calculated from the magnetic data and that given by the camera*. These are not explained.

We suggest that an experimental setup similar to the one used to evaluate the dynamic performance of the DGPS system and described in a separate report would be more appropriate.

Effect of Yaw and Roll Angle:

In order to determine the system's true accuracy, the effect of yaw and roll angles of the vehicle must be quantified. The report indicates that this was not done and is left for a future study.

Latency Issues:

We feel that one needs to know more about the computational latency of the filtering/prediction process in order to analyze the potential bandwidth (i.e. the speed of response) of the magnetic lateral position measurement system. The process of filtering the "raw data" from the magnetic sensor and determining the lateral position is computationally intensive. It would be worth checking into improving the sensor characteristics (e.g. linearity, bandwidth) through the design of appropriate special purpose DSP (Digital Signal Processor) chips. The added hardware would expedite the lateral position solution using parallelism and also assist in improving the specifications on the lateral indication system.

Noise and Bandwidth:

It is important to evaluate the reliability of the magnetic sensor and to determine whether there are sensor drop-outs (loss of measurement signals). There was no analysis of the effects of rebar and other potential disturbances of the tape's magnetic field. The problem of designing a higher bandwidth sensor should be examined as a function of the tape's magnetic wavelength (i.e. reduce the wavelength significantly or change the design to avoid a dependence on the tape's magnetic wavelength).

Longitudinal Position:

Although, the report mentioned that longitudinal information could be derived from the sensor, no attempts were made to devise such a computational procedure. An independent velocity sensor would be necessary to make this possible.

Differential Magnetometer Configuration and Yaw:

The report indicated that two magnetometers could be used to obtain yaw information (a recommendation to this effect, i.e. for using a pair of differential magnetometers, which would also reduce the effect of the earth's magnetic field, was suggested by us at the very beginning of the study), but this path was never pursued. This approach is highly recommended.

Experimentation under diverse conditions:

It is clear that bridges, overpasses and even highway signs present challenges that were absent in the Mn/ROAD study (even though the Mn/ROAD test road did have its own unique set of 'noise sources'). Experiments with the magnetic lateral position indication system need to be conducted under a variety of road environments and weather conditions to establish its robustness.

Encoding Preview:

Last but not least, it is necessary to allow preview information (i.e. upcoming road/lane curvature) to be encoded into the magnetic tape if we are to use the magnetic system either for an Automated Highway Systems (AHS) type application (with full automatic steering control) or for displaying the road curvature information to a driver in real time. This possibility was not considered in the 3M report. It should be considered in the future. For driver assistive

displays, the literature indicates that 1.1 seconds of preview is needed irrespective of speed for a human driver to react comfortably. This is discussed in our report entitled “Design of Human Centered Vehicle Control Systems.”

