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Testing of RTK-Level Satellite-Based Tractor Auto-Guidance Using a Visual Sensor System

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Preface

The importance of 3D-position sensors for the navigation of machinery on construction sites of roads, tunnels, railways, and airports has been steadily increasing over the last few years and the market keeps growing. Also, in the field of agricultural GPS-based applications, such as machine guidance, parallel tracking and yield mapping, new methods are introduced.

The main goal of the 1st International Conference on Machine Control & Guidance was to initiate the discussion of these topics among academics, researchers, system and service providers as well as users. The idea was to start a new conference series. The positive feedback on the first conference confirms the great interest on the topic of Machine Control & Guidance. As a consequence, the MCG-conference is now held for the second time.

This year, the conference will be hosted by the Faculty of Agriculture of the University of Bonn. Because of the traditional relationship between the Institute of Agricultural Engineering and the Institute of Geodesy and Geoinformation the agricultural applications are one focus of the conference.

Further thematic highlights of the 2nd Conference on Machine Control & Guidance are:

- Global Navigation Satellite Systems (GNSS)
- Inertial Navigation Systems (INS)
- Multi-Sensor-Systems
- System Control and Management
- Intelligent Mobile Machines
- Agricultural Applications

The organisers look forward to a variety of presentations, which will bring about fruitful discussions. Thus, this meeting will be a good opportunity to strengthen interdisciplinary cooperations between all participating communities. Finally, we would like to thank all authors, attendees and interested persons for their individual contributions.

Bonn, February 2010

Peter Schulze Lammers Heiner Kuhlmann
Testing of RTK-Level Satellite-Based Tractor Auto-Guidance Using a Visual Sensor System

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Abstract
The use of satellite-based positioning has advanced considerably in the world of agriculture, providing a range of technical solutions that include the automated steering of tractors and self-propelled machinery. With the development of auto-guidance systems comes the need to evaluate their performance. Given that current precision and accuracy claims are relatively small in magnitude, it is imperative there be a testing system capable of detecting errors with ten times greater accuracy—possibly as little as a few millimeters. A visual sensor was adopted to achieve this level of measurement resolution. The sensor was used to determine the cross-track error estimates necessary to summarize pass-to-pass and long-term levels of accuracy. To test a tractor with auto-guidance capability, the system was mounted to the tractor’s chassis to log the tractor’s relative position as it passed through the same course multiple times. Several different pilot tests have been conducted operating tractors at three travel speeds (1.0, 2.5 and 5.0 m/s). The values or guidance error estimates corresponding to 95% of the cumulative unsigned error distributions can serve as publicly acceptable test summaries. The results of this study can be used to pursue standardization of the auto-guidance test process.

Keywords
Auto-guidance, auto-steering, GNSS, visual sensor, tractor testing

1 INTRODUCTION
Auto-guidance (also known as auto-steering) technology that is based on global satellite navigation systems (GNSS) has been increasingly adopted around the world. Using auto-guidance, many field operations can be performed in a strict geometrical relationship with previous travel paths or other predefined geographical coordinates without direct inputs from an operator. Current auto-guidance systems available to producers have different levels of accuracy, sensor configurations and interfaces. Despite these differences, the performance of auto-guidance systems often involves an anticipated level of auto-guidance error frequently associated with what is called cross-track error (XTE). This error is caused by several factors: 1) geographic positioning errors; 2) vehicle dynamics; 3) the implement tracking behind the vehicle; and 4) field conditions. Manufacturers present different types of accuracy claims, making marketing comparison of their products difficult. Therefore, there is a need to develop a standardized procedure to test and report the performance of GNSS-based auto-guidance systems. The goal of this publication is to summarize the development of instrumentation and methodology for measuring auto-guidance error and to provide evaluation of the methodology developed using several tractors with different expected levels of auto-guidance accuracy when operated at various travel speeds.

The first step toward testing GNSS-based equipment included testing the GNSS receiver while stationary, as outlined by the Institute of Navigation (ION, 1997). For agricultural operations, it is important to test GNSS receivers while in motion (Stombaugh et al., 2002). Such test procedures fall into two categories: fixture-based (e.g., Taylor et al., 2004; Stombaugh et al., 2008) and on-vehicle (Han et al., 2004). To test GNSS-based navigation aids, Buick and Lange (1998) and later Buick and White (1999) compared the efficiencies of foam marker and GPS-based light bar guidance systems. Field efficiencies were determined by measuring the actual areas of skips and overlaps for different ground speeds and offline distances (based on vehicle track records). In another study, Ehsani et al. (2002) tested different GPS-based light bar systems by mounting them on the roof of a tractor and
driving nine swaths parallel to a pre-set A-B line. In both cases, an RTK receiver was used to determine the actual travel path.

The current challenge is the testing of GNSS Auto-Guidance systems, especially those with real-time kinematic (RTK) level accuracy (typically at the centimeter level). Instrumentation ten times more accurate than the tested system must be developed (ION, 1997); this demands measurement on the scale of millimeters. To meet this requirement non-GNSS-based measuring methods have been employed. For example, Harbuck et al. (2006) used optical surveying equipment to track a vehicle’s motion without involving GNSS-based equipment. A rugged 360-degree tracking prism was mounted to the towing hitch on the rear of the tractor. Position data was recorded using a total station equipped with a special function that allowed the moving prism to be followed using servo motors in its base. During each test, the tractor was operated through a straight pass using the auto-guidance system and the relative position of the tractor’s hitch was continuously recorded. The claimed 5 mm measurement error of the total station applicable for ideal conditions increased to 20 mm during the test.

Alternatively, Adamchuk et al. (2007) developed a linear potentiometer array that measured the horizontal position of a reference cart perpendicular to the direction of travel as it repeatedly passed over a series of stationary metal triggers installed on the surface of the pavement used for testing. The system had an approximate resolution of 20 mm; it did not rely on a GNSS signal. Although both methods are suitable for many non-RTK-based options, testing auto-guidance systems with a claimed accuracy of only 20 mm required a more precise solution.

2 MATERIALS AND METHODS

After considering several options involving different optical referencing techniques, the machine vision sensor approach was chosen. In this approach, a visual sensor rigidly mounted to the vehicle tested can be used to track the relative location of a permanent reference line on the surface of the test track. Repeated passes over the same track using zero swath width allow estimation of the horizontal distance between actual passes in each location of the track. In practical application, this would provide a means for assessing the anticipated level of skips and overlaps.

To test RTK-level systems, it can be expected that the level of errors would not exceed 0.5 m. To design the test system, a 1.2 m-field of view was assumed to be appropriate to allow the reference line on the surface to be seen by the visual sensor at all times. Achieving the 2-mm sensor resolution required by the 20-mm claimed accuracy would involve a 600 pixel-array (1200 mm / 2 mm) in the horizontal direction (perpendicular to the direction of travel). Therefore, a Cognex In-Sight® DVT 545 high speed vision sensor with internal processor (Cognex Corporation, Natick, Massachusetts)\(^1\) with a 9-mm lens was considered sufficient. The sensor had a 26° field of view and 640x1048 pixel array which was able to provide approximately 1.2 mm resolution at the testing surface when mounted 1.5 m above ground pointed downward. The sensor was also capable of automatically adjusting exposure and aperture settings for varying lighting conditions and processing images at about 30 frames/s. Visual sensor calibrations, cross-track position measurements and other adjustments were made using the Intellect™ (Cognex Corp., Natick, Massachusetts) software (Figure 1). As a result, the field of view of the vision sensor could obtain the relative position of a line marking the track.

Relative position measurements performed with the vision sensor were synchronized with geographic locations so that matching measurements could be obtained during different passes. An additional GNSS receiver was used to obtain geographic longitude and latitude, time and GNSS signal quality for further data processing. Data acquisition and storage was accomplished using a specially-developed LabVIEW® (National Instruments, Inc., Austin, Texas) interface.

Since most uses for auto-guidance are in the agricultural field, the test procedure developed was based on a typical field operation. This usually consists of a series of back and forth parallel passes across a certain distance. At the end of each pass, the vehicle is turned around and returns on a path adjacent to the previous pass offset by the fixed width of the implement (swath width). For the purposes of test development, XTE can be defined as the difference between the desired and actual

\(^1\) Mention of a trade name, proprietary product, or company name is for presentation clarity and does not imply endorsement by the authors or the University of Nebraska-Lincoln, nor does it imply exclusion of other products that may also be suitable.
swath widths. If the distance between two passes is less than the swath width, an overlap occurs; a
distance greater than the swath width produces a skip. Pass-to-pass error of auto-guidance is defined as
the relative XTE between two consecutive passes that occur within a 15 min timeframe. Long-term
auto-guidance error is defined as the relative XTE between two consecutive passes that occur more
than 1 hr apart with dissimilar GNSS satellite configurations in the sky.

Figure 1: The permanent reference line detected using the Intellect™ software.

To accommodate these definitions, each test consisted of three test runs with three passes about
7.5 min long made in alternating directions. For this type of testing, the test location needed to have a
surface that would remain consistent over time and would be replicable in other geographic areas.
Since tractor performance testing is typically done on concrete pavement, the same approach was
taken to help develop the auto-guidance system test procedure. The concrete tractor test track of the
Nebraska Tractor Test Laboratory (NTTL, Lincoln, Nebraska) was selected (Figure 2).

Figure 2: Test Track of the Nebraska Tractor Test Laboratory

The track consists of two east-west oriented straight passes separated by 39.9 m (131 ft). Both
passes are relatively level, with the total length of the central line around the track being
approximately 615 m (2018 ft). Each straight pass of the track is 6.7 m (22 ft) wide with an expansion
seam in the middle. This seam was designated as the permanent reference line. To adapt the ideal
(back and forth) field operation pattern to the geometry of the test track, the test trial consisted of
sequential counterclockwise and clockwise laps around the track as shown in Figure 3. The initial A-B
line was established along the northern pass and the auto-guidance equipment was set with a 39.9 m
swath width. The tested tractor was operated in auto-guidance mode along each of the two passes.
During each pass, the relative location of the tractor’s representative vehicle point (RVP) with respect
to the reference line was measured. For each location around the track, the difference between these
relative position measurements (adjusted for the direction of travel) was used to define the relative
XTE.
The decision was made to use test vehicles offering the most common platform on which auto-guidance systems are installed. Mechanical front wheel assist tractors in the range of PTO power from 110 to 220 kW (150 to 300 hp) were selected. The drawbar hitch pin hole was designated as the RVP for these vehicles. Figure 4 shows the vision sensor rigidly mounted to the chassis of the tractor with the lens pointed downward so that the field of view was centered on the drawbar hitch pivoting location. Calibration of the vision sensor was accomplished with a Cognex® 100-mm calibration grid centered under the hitch pin hole with the horizontal axis parallel to the rear axle of the tractor. With the sensor mounted and calibrated, a reference receiver was fitted to the test tractor and the offset from the drawbar hitch pin hole was measured.

At the start of each test run, the tractor was located at the northeast corner of the track facing west (ready to travel in a counterclockwise direction around the track). The data acquisition system was started, the tractor moved forward, and the auto-guidance system engaged. The tractor traveled...
along the north side of the track with a swath width of 0 m with respect to the original A-B line until it reached the end of the northern pass. At the curve, the tractor was manually driven counterclockwise around the western curve of the track and lined up with the expansion seam of the southern portion of the track. As the tractor entered the southern pass, the auto-guidance system was engaged with a swath width of 39.9 m from the original A-B line. The auto-guidance mode remained engaged along the southern pass of the track until the tractor reached the eastern end. The operator again took control and manually steered the tractor around the curve. At this point, depending on the lap number and the number of laps required by the test speed, the tractor either turned around to travel in a clockwise (CW) direction or continued forward to complete the number of counterclockwise laps required for that travel speed. Travel speeds were 1.0, 2.5 and 5.0 m/s. To account for increased travel distances due to higher speed, the tractor performed several laps in the counterclockwise, clockwise, and counterclockwise direction so the travel time in one direction was just above 7.5 min.

As the tractor was entering into a new straight pass, the auto-guidance mode was engaged before the end of the curve unless the travel direction changed from clockwise to counterclockwise. In this situation, the auto-guidance mode was engaged before a set point on the northern side of the track. Data taken before this point was excluded from the analysis. To process the data, average valid relative position and time measurements were obtained for each 1-m segment of the track. Relative XTE terms were found by comparing relative position measurements (sensor output) between two collocated points from different passes in a single test run that were in the opposite direction with under 15 min revisit time for the pass-to-pass error. Long-term error was found by comparing cross-track position measurements between passes in opposite directions but from different test runs.

From the unsigned values of relative XTE, cumulative distributions were constructed with 95% errors identified. Mean values of signed XTE were calculated to determine bias in the auto-guidance system. This paper provides results from tests of three different tractors with auto-guidance options (Table 1). Although the test procedure was very similar, there were modifications to the test system and differences in the time of year which might influence test results. Thus, these results cannot be used to make a fair comparison of these systems. Test runs were performed in a randomized order at randomized times with the stipulation that at least 1 hr separated same speed test runs, and same speed test runs were not performed with a 24 hour time difference to avoid similar satellite configurations.

<table>
<thead>
<tr>
<th>System ID</th>
<th>GNSS Receiver</th>
<th>System Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RTK-level</td>
<td>WAAS* Advanced controller, proper calibration, dual tires</td>
</tr>
<tr>
<td>2</td>
<td>RTK-level</td>
<td>RTK Old controller, no calibration, dual tires</td>
</tr>
<tr>
<td>3</td>
<td>RTK-level</td>
<td>WAAS Quick calibration, single tires</td>
</tr>
</tbody>
</table>

* - Wide Area Augmentation System

Because of the differences between systems, it was expected that the tractors would perform differently when operated using the same test procedure. System 1 represents one of the most accurate options available to producers with proper calibration prior to the test. System 2 had the disadvantage of a less-advanced controller and no system calibration prior to the testing. Likewise, System 3 was not fine-tuned prior to the test.

3 RESULTS AND DISCUSSION

In using the proposed test procedure, there were initial concerns that the pass-to-pass error estimates would not represent the even revisit time distribution for the entire 15 min interval. However, as shown in Figure 5 (the System 1 test), the revisit time distribution had relatively similar occurrences from 1 to 15 min. The reduction of revisit times below 1 min was due to the time required to turn around. (This could also be expected during field operations.) The observed cycling patterns related to use of the eastern and western ends of the track to switch between the northern and southern
passes. Also, it was noted that a faster travel speed presented more 1-m section revisit incidents than a slower travel speed, due to the differing number of time-based measurements averaged for each 1-m section. The reason for the 1-m partitioning of test passes was the anticipated error of the GPS receiver used for georeferencing. Time-based averaging was thought to be inappropriate because of the practical value of the geometrical performance of the testing (that is, the predictability of skips and overlaps).

![Figure 5: Revisit time distributions at three different travel speeds.](image)

Table 2 summarizes auto-guidance error distributions associated with each system test and travel speed. First, the average signed error measurements were much smaller than the standard deviation, indicating that none of these systems had significant bias (pull of the tractor to one side). Also, it should be noted that error estimates at 1.0 and 2.5 m/s were similar, and higher numbers at 5.0 m/s were observed. This indicates that testing at a relatively low speed (e.g., 1.0 m/s) might not be necessary, whereas determination of the system’s performance at a higher speed is needed. Also, pass-to-pass and long-term error estimates were similar because of relative day-to-day stability or RTK-level positioning. Similar observations can be made when evaluating the cumulative unsigned error distributions (Figure 6).

<table>
<thead>
<tr>
<th>Test speed, m/s</th>
<th>System ID</th>
<th>Pass-to-Pass Error, mm</th>
<th>Long-Term Error, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Signed distribution</td>
<td>Unsigned distribution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>1.0</td>
<td>1</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-1</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>2.5</td>
<td>1</td>
<td>-1</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-3</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>59</td>
</tr>
<tr>
<td>5.0</td>
<td>1</td>
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<td>20</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>51</td>
</tr>
</tbody>
</table>
In general, System 1 represents the best possible performance observed using the equipment and methodology developed. Both pass-to-pass and long-term errors were under 20 mm 95% of time when traveling at 1 and 2.5 m/s. Higher travel speed caused an error increase, mainly because of the longer distance requirement to come to a steady-state operation along a straight path. The lower-end controller and poor calibration caused the performance of System 2 to yield less than 50 mm errors 95% of the time, which also increased at 5 m/s. System 3, on the other hand, showed a more gradual increase in pass-to-pass errors from 54 to 100 mm with speed; this could also be attributed to relatively poor system fine-tuning prior to the test on concrete pavement.
4 CONCLUSIONS

A visual sensor-based system was developed to test the performance of tractors capable of operating in auto-guidance mode using RTK-level GNSS receivers. By design, the test system was capable of detecting differences of less than 2 mm. Pass-to-pass and long-term cross-track errors were defined as the ability of the system to repeat the same pass in an opposite direction within short (15 min) and long (several hour) time periods. A test summary for three different travel speeds and three different auto-guidance systems shows that the test system developed can differentiate among operating conditions that may affect auto-steering performance.

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