Computers and Electronics in Agriculture 72 (2010) 107–118

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Using a vision sensor system for performance testing of satellite-based tractor auto-guidance

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ARTICLE INFO

Article history:
Received 3 July 2009
Received in revised form 3 February 2010
Accepted 16 March 2010

Keywords:
Auto-guidance
Auto-steering
GNSS
GPS
Receiver
Tractor testing
Standard

ABSTRACT

A vision sensing system for the measurement of auto-guidance pass-to-pass and long-term errors was implemented to test the steering performance of tractors equipped with auto-guidance systems. The developed test system consisted of an optical machine vision sensor rigidly mounted on the rear of the tested tractor. The center of the drawbar hitch pin point was used as the reference from which to measure the deviation of the tractor's actual travel path from its desired path. The system was built and calibrated to a measurement accuracy of better than 2 mm. To evaluate the sensor, two auto-guidance systems equipped with RTK-level GNSS receivers were tested and the results for different travel speeds compared. Pass-to-pass and long-term errors were calculated using the relative positions of a reference at a collocated point when the tractor was operated in opposite directions within 15 min and more than 1 h apart, respectively. In addition to variations in speed, two different auto-guidance steering stabilization distances allowed for comparison of two different definitions of steady-state operation of the system. For the analysis, non-parametric cumulative distributions were generated to determine error values that corresponded to 95% of the cumulative distribution. Both auto-guidance systems provided 95% cumulative error estimates comparable to 51 mm (2 in.) claims and even smaller during Test A. Higher travel speeds (especially 5.0 m/s) significantly increased measured auto-guidance error, but no significant difference was observed between pass-to-pass and long-term error estimates. The vision sensor testing system could be used as a means to implement the auto-guidance test standard under development by the International Standard Organization (ISO). Third-party evaluation of auto-guidance performance will increase consumer awareness of the potential performance of products provided by a variety of vendors.

1. Introduction

Auto-guidance (also called auto-steering) systems represent a rapidly expanding technology in precision agriculture that is based on the use of global navigation satellite system (GNSS) receivers to perform field operations in a strict geometrical relationship with a previous travel path or other predefined geographical coordinates, without direct inputs from an operator. Although auto-guidance systems available to producers have different levels of operation accuracy as well as sensor configurations and interfaces, their performance is frequently associated with an anticipated level of auto-guidance error, usually referred to as cross-track error (XTE). This error can be attributed to numerous uncertainties, including: (1) geographic positioning errors; (2) vehicle dynamics; (3) the implement tracking behind the vehicle; (4) the field environment (slopes, soil condition, etc.). Manufacturers of auto-guidance systems publish claims that rely on a variety of different test procedures, and as a result, consumers cannot use marketing information to compare the performance of different products. Therefore, there is a need to develop a standardized procedure to test and report the performance of GNSS-based auto-guidance systems.

The first step in testing GNSS-based equipment involves evaluation of the static performance of GNSS receivers by placing the antenna in a fixed georeferenced location (ION, 1997) and logging measurements made by the receiver. Agricultural operations are dynamic in nature; therefore, tests of GNSS receivers used in agriculture should be performed while in motion. Stombaugh et al. (2002) and later Stombaugh et al. (2008) provide general guidelines for a dynamic test. Two main dynamic GNSS receiver testing

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doi:10.1016/j.compag.2010.03.004

methods were defined: (1) fixture-based testing, which involves mounting the GNSS receiver on a platform that is operated along a fixed path with known geographic coordinates and (2) vehicle-based testing, in which the tested set of receivers is placed on the top of a vehicle along with a superior performance measurement system, possibly a real-time kinematic (RTK) GNSS receiver. Advantages of fixture-based testing include the ability to calculate errors with respect to the actual (surveyed) geographic coordinates and the repeatability of the testing procedure. The advantage of vehicle-based testing is it can represent actual field operations.

Though fixture-based testing cannot be used to evaluate the actual performance of a vehicle operated using a GNSS receiver, Han et al. (2004) implemented a vehicle-based approach to test eight commercially available DGPS receivers from four different manufacturers with five alternative differential correction services. All eight tested GPS receivers were mounted simultaneously on a test vehicle at least 1 m apart from each other to reduce possible signal interference. An RTK-level GPS receiver was mounted in the center of the test platform to provide the vehicle reference positions. The vehicle was manually driven on a travel path as straight as possible in the north-south direction, with each test consisting of six parallel passes approximately 305 m (1000 ft) long. The desired pass-to-pass spacing was 6.10 m (20 ft). Off-track errors were determined as the root mean squared difference between the horizontal position determined by the reference receiver (with the appropriate offset compensations) and the tested receivers. Pass-to-pass error was defined as the difference between corresponding off-track errors. It was noted that travel speed might play an important role in quantifying receiver accuracy since at lower speeds, the pass-to-pass average errors tended to be larger. Han et al. (2004) associated the increase in pass-to-pass error with the longer time needed to complete the test course when moving slower. However, due to data limitations, complete analysis of the effect of travel speed was not conducted.

A similar approach can be used to test the performance of navigation aids, known as light bar systems. Light bar systems assist the operator of an agricultural vehicle in steering it according to GNSS position estimates. 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 testing of auto-guidance systems has become the latest challenge when it comes to the GNSS-based operation of agricultural vehicles. The measurement system for test instrumentation must have at least ten times greater accuracy than the system being tested (ION, 1997). This means that for auto-guidance systems equipped with meter and decimeter-level GNSS receivers, a centimeter-level sensor, such as an RTK-level GNSS receiver, can be used. However, since many advanced auto-guidance options employ centimeter-level GNSS receivers, an appropriate test system should be capable of making millimeter-level measurements.

Harbuck et al. (2006) employed optical surveying equipment to track vehicle motion without the involvement of 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 made it possible to follow the moving prism by the use of servo motors in the total station base. During each test, the tractor was operated through a straight pass using the auto-guidance system, and the relative position of the tractor hitch was continuously recorded. The claimed 5-mm measurement error of the total station was applicable under ideal conditions, but this error increased to 20 m during the test. Consequently, the order of magnitude required for greater accuracy by the measurement system was no longer valid.

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 and 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 around 20 mm would require a more precise solution.

The objectives of this research were (1) to develop instrumentation and test methodology for measuring relative XTE with millimeter-level accuracy; (2) to evaluate the method developed by comparing the performance of tractors with auto-guidance systems operated at various travel speeds; (3) to recommend a test procedure for measuring pass-to-pass and long-term relative XTE in a repeatable manner.

2. Materials and methods

2.1. Instrumentation development

Testing auto-guidance systems requires a method of measurement that is accurate enough, yet easy to use and adaptable to multiple situations. After a number of options involving different optical referencing techniques were considered, the final choice was the machine vision approach. Various machine vision sensors are used extensively in industry for real-time monitoring of product dimensions and quality control. Following a test concept pursued by Adamchuk et al. (2007), the vision sensor was mounted on the tested vehicle to monitor a permanent reference line on the pavement below. As the vehicle moved along the test track, it was possible to measure the relative position of the tested vehicle with respect to the permanent reference line in every location along the test track.

Since the test was focused on auto-guidance systems with RTK-level GNSS receivers, a 1.2-m field of view was assumed appropriate so that the line remained visible to the sensor during the entire test. To achieve 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). A Cognex In-Sight® DVT 545 high-speed vision sensor with an internal processor (Cognex Corporation, Natick, MA)[4] and a NAV LFC-9F1B 9-mm lens was considered sufficient. The sensor had a 640×1048 pixel array with a 26° field of view. This provided approximately 1.2-mm resolution at the testing surface when mounted 1.5 m above the ground and pointed downward. The sensor was capable of automatically adjusting exposure and aperture settings for varying lighting conditions and could process images at the rate of approximately 30 frames/s. The vision sensor calibration, cross-track position measurements, and other adjustments were made using Intellect™ (Cognex Corp., Natick, MA) software.

Relative position measurements performed with the vision sensor were synchronized with geographic locations to allow the matching of measurements obtained during different passes. An additional GNSS receiver was used to obtain geographic longitude

[4] 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.