A Self Calibrating Attitude Determination System for Precision Farming using Multiple Low-Cost Complementary Sensors

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Abstract
A low cost three axis attitude determination system for moving platforms has been developed by Leica Geosystems that requires a minimal calibration procedure, and has the ability to self-calibrate for the various biases caused by temperature variation and mounting misalignment.

Sensor fusion techniques are used to combine the data from a high quality survey grade GNSS receiver with additional cost effective high performance inertial sensors to produce a high rate of attitude data with low noise and low bias in the form of an attitude sensor module for machine control and guidance applications.

The sensor module has been successfully integrated into a tractor steering system for precision farming.

This paper demonstrates the minimal installation and calibration procedures for the system, and presents the results from benchmarking the system in real farm operating conditions.

Keywords
GPS, agriculture, precision farming, tractor, Leica, mojoRTK

1 INTRODUCTION
The benefits of machine guidance systems are well known within the field of precision agriculture. These may include increased yield from crops, reduced input costs due to overlap, reduced driver fatigue and reduced fuel usage [Webb, 2004].

Modern GPS equipment is capable of producing high quality position measurements with standard deviations of less than one inch and update rates faster than ten times per second, however, this alone is not sufficient for accurate tractor guidance. The terrain on farms is rarely smooth and flat, and this means that a GPS antenna mounted in the roof of a tall vehicle such as a tractor will experience movement relative to the ground position as the vehicle pitches and rolls over uneven terrain.

The use of two or three axis attitude solutions to compensate for lever arm effect of the GPS antenna [Korver, 1999] is frequently practiced within the field of precision agriculture. The literature refers to this as “terrain compensation” or “tilt compensation”. The benefits of this include increased on-line accuracy in rough terrain [Ag Leader, 2005] as well as a reducing skips and overlaps between passes on sloped and undulating country [Trimble, 2005].

Agricultural guidance systems typically calculate vehicle attitude using a combination of inertial sensors [Trimble, 2005], or multiple GPS antennas [O’Connor, 1996], and each approach has strengths and weaknesses. Inertial based attitude solutions are subject to errors caused by sensor biases, axis misalignment, scale factor biases and temperature drift. A purely GPS-based attitude solution does not have these sensor biases, but does experience the availability and signal outage problems associated with GPS positioning.
The Leica mojoRTK system makes use of automotive grade MEMS inertial sensors and a dual frequency survey grade GPS/GLONASS receiver to provide position and attitude information that is suitable for agricultural guidance and machine control applications.

This paper focuses specifically on the roll of the vehicle, since it is the quantity of most interest for a terrain compensation system.

### 1.1 System Overview

The mojoRTK sensors consist of three rate gyros, a three axis accelerometer package and a digital compass. In addition to these sensors, the system includes two GPS receivers that produce a two axis attitude solution which is used for estimating the biases of the inertial sensors.

![Figure 1: System Sensor Architecture](image)

#### 1.1.1 Installation

The installation of the mojoRTK system into a vehicle is relatively simple. First, the two GPS antennas are stuck to the roof of the vehicle. The antennas are mounted in such a way that a line through the centres of the antennas is parallel to the left-right axis of the vehicle. Antenna cables then are routed into the cab of the tractor. After the antennas are installed, the mojoRTK console is installed into the radio slot of the tractor. The mojoRTK console contains the inertial sensors and other electronics.

![Figure 2: Installation Diagrams from the mojoRTK User Manual](image)

#### 1.1.2 Calibration

The calibration of the mojoRTK system is conducted by performing two manoeuvres with the vehicle. The first manoeuvre involves sitting the vehicle in a stationary position for a short period of time, then rotating the vehicle 180 degrees in the same location. This allows the system to estimate the roll and pitch orientation of the mojoRTK console within the vehicle reference frame, and estimate the bias of
the accelerometers. The yaw orientation is manually entered by the operator and is usually zero or +/- 90 degrees, depending on the location of the radio slot. The second manoeuvre requires the operator to drive the vehicle in a slow circle in order to calibrate the digital compass for the hard iron effects from the tractor.

Once this initial calibration procedure has been performed, the system continues to improve the calibration information using the attitude solution provided by the two GPS antennas. This allows a profile to be built up for the temperature dependant biases and adjusts the calibration over time to account for sensor aging effects.

2 SYSTEM TESTING

The inertial sensors used on the mojo console are automotive grade MEMS sensors. The manufacturing processes used for MEMS sensors produce relatively large variances in the bias and scale factor for the sensor measurements. Several techniques have been implemented in the mojo firmware to account for these biases. This test evaluated the quality of the sensor measurements after these corrections had been applied, and the quality of the attitude solution used in terrain compensation for the GPS antenna position. The goal of this test was to collect and analyse attitude data from a mojo console by using an independent measure of the vehicle roll.

2.1 Test Setup

The vehicle attitude was measured in the roll axis using two survey grade GPS receivers producing RTK positions at 10Hz.

Two GPS antennas were attached to the chassis of the tractor with a steel frame. Leica AT-504 choke ring antennas are used. The separation between the antennas was 3.00 meters. The frame was rigidly attached to the vehicle body by using the bolts on the roof of the tractor. There was no noticeable vertical flexibility in the structure, which meant that the precision of the roll benchmark measurement is limited to the uncorrelated vertical noise of the GPS position, which accounts to roughly 0.4 degrees measurement noise.

The two attitude GPS antennas are each connected to a survey grade GPS receiver, and real-time kinematic carrier phase position solutions are calculated for each antenna, using a common base station located approximately 100 meters away. The attitude solutions are processed from these two positions only when integers are fixed for both antennas.

In addition to the attitude GPS antennas, a mojoRTK console was installed in the vehicle in the standard configuration. The mojoRTK console was set to log raw inertial data at 100Hz, and attitude solutions at 10Hz. This was the source of the attitude data evaluated in this document.


2.2 Data Collection

Two scenarios were used to collect the data from the “Long Hill” farm, located near the town of Boonah (28.097853º South, 152.657275º East) on the 4th of March 2008.

The first test scenario involved driving along the northern fence of the field, and driving over a large bump that rolls the vehicle from zero to 6 degrees roll over a distance of approximately 2 meters along the row. The second test scenario involves driving the more gentle slopes parallel to the eastern fence of the field.

Each of the scenarios involved driving the tractor along one row then returning in the opposite direction along the next parallel row. After 30 minutes, the direction of travel was reversed. The duration of data collection was approximately one hour for each scenario.

Figure 4: Test Scenario Orientation

2.3 Data Processing

2.3.1 GPS Attitude Calculation

The positions of the left and right antennas are stored in Cartesian ECEF coordinates, and time-tagged with GPS time. The positions are differenced in the ECEF frame.

\[ P_1 = [x_1, y_1, z_1] \]
\[ P_2 = [x_2, y_2, z_2] \]
\[ \Delta P = P_2 - P_1 \]

Where: \( P_1 \) is the ECEF position of the left antenna and \( P_2 \) is the ECEF position of the right antenna

The differenced positions are then rotated to the local navigation frame (east-north-up coordinates) using the following transform:

\[ \Delta B = \Delta P \times M = [b_e, b_n, b_u] \]
Where:

\( \Delta B \) is the difference between the two antenna positions in the local (east-north-up) frame,

\( M \) is the direction cosine matrix to rotate between ECEF and ENU reference frames.

The GPS-derived roll is calculated as follows:

\[
roll = \sin^{-1}\left( \frac{b_{uy}}{|\Delta B|} \right)
\]

### 2.3.2 Data Synchronisation

The attitude data from the mojo console is time-tagged according to the system kernel time at which the inertial measurements were received by the microprocessor. This system time is stored in the data log files. In addition to this, the GPS data for the mojo console is tagged with both the system time, GPS week and the GPS seconds of week.

The GPS attitude solutions are matched to the correct system time on the mojo console by searching the log file for the corresponding GPS time tags. This allows the both the inertial and the GPS attitude solutions to be plotted using the system kernel time as the common time scale.

### 3 RESULTS

The following sections show the IMU roll plotted alongside the matching GPS roll solutions. The timescale is in seconds since the mojoRTK console was powered on. Several views are presented at different zoom levels to show long term and short term variations.

#### 3.1 Results from Scenario 1

![Figure 5: GPS and IMU roll for Scenario 1 – Wide View](image)

![Figure 6: GPS and IMU roll for Scenario 1 – Zoomed View](image)
Roll Difference mean $\mu = -0.2585$ degrees
Roll Difference Standard Deviation $\sigma = 0.5232$ degrees

3.2 Results From Scenario 2

Roll Difference mean $\mu = -0.1878$ degrees
Roll Difference Standard Deviation $\sigma = 0.5287$ degrees
4 CONCLUSIONS

The results in the previous section show that performance of the roll calculation from the mojoRTK inertial sensors is very close to the measurable precision of the GPS attitude benchmarking system. This is achieved at a much lower cost to performance ratio because of the cost effective sensors that are used in the system.

The mean error for the roll calculations is 0.2585 degrees in the worst case of scenario 2, which translates to a 13.5mm mean pass to pass position error (based on a 3 meter tall vehicle) due to roll error. The roll noise with standard deviation of 0.5287 degrees translates to a lateral roll compensation noise of 27.6mm. This is only slightly larger than the expected measurement noise of the GPS roll calculation.

Overall, the accuracy of the roll calculation meant that the system performs successfully within the performance requirements of the mojoRTK product by satisfying the 50mm positioning accuracy of the terrain compensated position on the ground.

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