DYNAMIC EVALUATION OF THREE GPS RECEIVERS ON THE CONTROL PERFORMANCE OF AN AUTONOMOUS VEHICLE DEVELOPED WITH PURE PURSUIT SYSTEM ARCHITECTURE

by

ADAM GERALD FAIRCLOTH

(Under the direction of Glen Rains)

ABSTRACT

As population growth puts demands on increased food production and farmers are experiencing smaller profit margins, new crop production management practices are being explored. Precision farming and genetically modified crops are examples of new technologies being developed to help improve crop production. Two of the technologies currently in use are global positioning systems (GPS) and automatic guidance. The purpose of this study was to develop an autonomously driven tractor controlled through the use of GPS information. In addition three GPS systems of varying accuracy and cost were used and compared. The control approach used was a pure pursuit or goal seeking method. The control structure proved to work effectively. The best performing GPS system was the Trimble RTK-GPS system. An OmniSTAR-HP receiver and a WAAS receiver were also used in this study.

INDEX WORDS: Precision agriculture, Autonomous guidance, GPS, RTK-GPS, OmniSTAR-HP, WAAS, Goal seeking
DYNAMIC EVALUATION OF THREE GPS RECEIVERS ON THE CONTROL PERFORMANCE OF AN AUTONOMOUS VEHICLE DEVELOPED WITH PURE PURSUIT SYSTEM ARCHITECTURE

by

ADAM GERALD FAIRCLOTH
B.S., University of Georgia, 2002

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA
2004
DYNAMIC EVALUATION OF THREE GPS RECEIVERS ON THE CONTROL PERFORMANCE OF AN AUTONOMOUS VEHICLE DEVELOPED WITH PURE PURSUIT SYSTEM ARCHITECTURE

by

ADAM GERALD FAIRCLOTH

Approved:

Major Professor: Glen Rains

Committee: Chi Thai
            Randy Raper

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
August 2004
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION AND LITERATURE REVIEW</td>
<td>1</td>
</tr>
<tr>
<td>2 EVALUATION OF A PURE PURSUIT SYSTEM ARCHITECTURE FOR AN AUTONOMOUS, ARTICULATED-STEER VEHICLE</td>
<td>8</td>
</tr>
<tr>
<td>3 DYNAMIC ANALYSIS OF THREE GPS SYSTEMS OF VARYING ACCURACY</td>
<td>36</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>56</td>
</tr>
<tr>
<td>APPENDIX A: USER INTERFACES FOR CONTROL PROGRAMS</td>
<td>58</td>
</tr>
<tr>
<td>APPENDIX A-1: FRONT PANEL OF TRACTOR CONTROL PROGRAM DEVELOPED IN LABVIEW, VERSION 6.1</td>
<td>59</td>
</tr>
<tr>
<td>APPENDIX A-2: FRONT PANEL OF PROGRAM TO GATHER GPS AND SENSOR DATA, DEVELOPED IN LABVIEW, VERSION 6.1</td>
<td>60</td>
</tr>
<tr>
<td>APPENDIX B: FLOW DIAGRAMS FOR CONTROL ALGORITHMS</td>
<td>61</td>
</tr>
<tr>
<td>APPENDIX B-1: FLOW DIAGRAM OF TRACTOR CONTROL ALGORITHM</td>
<td>62</td>
</tr>
<tr>
<td>APPENDIX B-2: SEQUENCE STRUCTURE FOR TRACTOR CONTROL ALGORITHM</td>
<td>63</td>
</tr>
<tr>
<td>APPENDIX B-3: SEQUENCE 0</td>
<td>64</td>
</tr>
<tr>
<td>APPENDIX B-4: SEQUENCE 1</td>
<td>65</td>
</tr>
<tr>
<td>APPENDIX B-5: SEQUENCE 2</td>
<td>66</td>
</tr>
</tbody>
</table>
LIST OF TABLES

TABLE 2.1. Position and heading data compared with maximum path deviation for Path 5, used for program evaluation.................................................................21

TABLE 2.2. Example data from Path 1 with speed setting of 5 km/h and Full Pulse rate, used for program evaluation .................................................................22

TABLE 2.3. Difference in distance covered using average time from Table 2.2 and Speeds 1 and 2.................................................................................................23
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>TEST VEHICLE</td>
</tr>
<tr>
<td>2.2</td>
<td>Overhead depiction of test vehicle with wheelbase dimensions</td>
</tr>
<tr>
<td>2.3</td>
<td>Basic components of system architecture</td>
</tr>
<tr>
<td>2.4</td>
<td>Description of Control Equation Relationship</td>
</tr>
<tr>
<td>2.5</td>
<td>Representation of Radius and Voltage Relationship</td>
</tr>
<tr>
<td>2.6</td>
<td>Mean error and 95% confidence interval for all pulse rate combinations at 2.4 km/h</td>
</tr>
<tr>
<td>2.7</td>
<td>Relationships for tractor with respect to Path 5, corresponding to Table 2.1</td>
</tr>
<tr>
<td>2.8</td>
<td>Demonstration of problems that occur by calculating heading from GPS data when speed of vehicle is too fast for the control algorithm</td>
</tr>
<tr>
<td>2.9</td>
<td>Data points for Path 1 at Full Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.10</td>
<td>Data points for Path 1 at Half Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.11</td>
<td>Data points for Path 1 at Quarter Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.12</td>
<td>Data points for Path 2 at Full Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.13</td>
<td>Data points for Path 2 at Half Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.14</td>
<td>Data points for Path 2 at Quarter Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.15</td>
<td>Data points for Path 3 at Full Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.16</td>
<td>Data points for Path 3 at Half Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.17</td>
<td>Data points for Path 3 at Quarter Pulse rate and Speed 1</td>
</tr>
<tr>
<td>2.18</td>
<td>Data points for Path 4 at Full Pulse rate and Speed 1</td>
</tr>
</tbody>
</table>
FIGURE 2.19. Data points for Path 4 at Half Pulse rate and Speed 1 ...........................................32
FIGURE 2.20. Data points for Path 4 at Quarter Pulse rate and Speed 1 ...........................................32
FIGURE 2.21. Data points for Path 5 at Full Pulse rate and Speed 1 ...........................................33
FIGURE 2.22. Data points for Path 5 at Half Pulse rate and Speed 1 ...........................................33
FIGURE 2.23. Data points for Path 5 at Quarter Pulse rate and Speed 1 ...........................................34
FIGURE 2.24. Data points for Path 1 at Full Pulse rate and Speed 2 ...........................................34
FIGURE 2.25. Data points for Path 2 at Full Pulse rate and Speed 2 ...........................................35
FIGURE 3.1. Test vehicle ............................................................................................................41
FIGURE 3.2. Basic components of systems architecture ............................................................42
FIGURE 3.3. Trimble AgGPS 214 receiver with antenna ...........................................................42
FIGURE 3.4. NovAtel ProPak-LB receiver ................................................................................43
FIGURE 3.5. Trimble AgGPS 132 receiver with antenna ...........................................................43
FIGURE 3.6. Trimble AgGPS 114 receiver / antenna .................................................................44
FIGURE 3.7. Test area where test trials were performed ............................................................46
FIGURE 3.8. Mean error and +/- 95% confidence interval for Paths 1-5 with
OmniSTAR-HP system used as control .....................................................................................48
FIGURE 3.9. Mean positions for all GPS systems, Path 1 ..........................................................50
FIGURE 3.10. Mean positions for all GPS systems, Path 2 ..........................................................51
FIGURE 3.11. Mean positions for all GPS systems, Path 3 ..........................................................51
FIGURE 3.12. Mean positions for all GPS systems, Path 4 ..........................................................52
FIGURE 3.13. Mean positions for all GPS systems, Path 5 ..........................................................52
CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

As population growth puts demands on increased food production and farmers are experiencing smaller profit margins, new crop production management practices are being explored. Precision farming and genetically modified crops are examples of new technologies being developed to help improve production. Precision Agriculture, in reference to site-specific crop production, as defined by the Australian Centre for Precision Agriculture is “matching resource application and agronomic practices with soil attributes and crop requirements as they vary across a field” (ACPA, 2003). Essentially, the goal of precision agriculture is to develop methods and techniques that maximize available farmer resources.

The desire to be able to perform farming tasks with accuracy and repeatability within a field lead to the introduction of global positioning system (GPS) technology in agriculture. GPS is a navigation tool developed by the U.S. Armed Forces (Dana, 2000). The system is available for use by both the military and civilian populations. The three components of the system are a constellation of satellites, monitoring stations, and receivers. Receiver positions are determined by calculating the relative distance from the receiver to four or more satellites. Monitoring stations keep the orbital data and clock corrections updated for each satellite in the constellation. Currently, there are 27 satellites in the earth’s atmosphere (Langley, 2003). According to Kvien (2002), “using GPS for guidance and tracking of equipment and field documentation” has shown to be a useful tool in the realm of precision agriculture. One area of considerable research is the
development of variable rate irrigation processes. Perry and Pocknee (2002) have effectively used GPS technology to determine the position of center pivots within a field. Knowing the position of the pivot in conjunction with predetermined map areas, the amount of water applied to the field can be varied according to need. Another area where GPS systems are used is yield mapping. When used in conjunction with a yield monitor, GPS allows farmers to determine which areas of fields produce the best and worst yields (Shannon et al., 2002). GPS technology has also become increasingly important in the realm of automatic guidance for agricultural equipment including sprayers, tillers, harvesters, etc. The technology has helped to reduce problems such as row overlap by human operators. According to one source, automatic guidance systems have helped to increase productivity by 3 to 5 percent solely from reduction of overlap (Naegely, 2001).

Automatic guidance has been studied several years with different sensors used for position and attitude adjustment. One area of research used laser positioning for guidance applications. Hague described such systems that use a vehicle mounted laser and three or more detectors within the field of motion. Based upon the relationship between the laser and the detectors, the position of the vehicle was determined through triangulation (Hague et al., 2000). Other systems use a more mechanically based sensor approach. Yekutieli and Pegna (2002) developed an automated vehicle for use in vineyards. The vehicle’s guidance system operated through the relationship of the sensors and wires that are strung along the course of the vine rows. Upchurch et al. (1983) also developed a mechanically based system for use on an orchard harvester. In order to accurately control the motion of the harvester, sensors providing input regarding the relationship of the trees’ position to the centerline of the vehicle relayed
information to the onboard processor. The processor then determined the correct steering adjustments to be made. Yet another area of research bases the vehicles’ operation on imaging techniques. Okamoto et al. (2002) developed a vehicle that determined the position of crop rows in order to ensure that the vehicle followed the correct path. Another method of employing machine vision was developed by Amidi (1990). He showed that by determining the position of the road ahead, the vehicle could be made to accurately follow the road.

GPS technology on the other hand is already in use by farmers for yield monitoring, crop spraying, and hunting. When developing automated systems, researchers and companies alike are pursuing methods that will provide the most accurate position, while limiting the cost to the consumer. Included in this category are both autonomous and automated guidance systems. According to Han and Zhang (2001), autonomous tractors should have the ability to automatically control all steering and implement functions. Automated tractors conversely require input from operators to perform functions such as end of the row turning and traveling to the field. The central goal of both approaches is to limit the amount of operator error and to allow the operator time for other tasks. Autonomous systems are probably the best approach for achieving both of these goals due to the fact that the operator’s presence is not required. With the use of autonomous tractors, farmers can tend to equipment in totally different vicinities. Some autonomous vehicles have been developed, but as of yet no vehicles are commercially available.

Led by the decline in the number of qualified machine operators in Japan, Noguchi et al. (2001) developed an autonomous tractor that used RTK-GPS guidance that could accurately
follow straight and curved paths at up to 2.5 m/s. Similar research has been performed at other research institutions (Han and Zhang, 2001; Nagasaka et al., 2002).

Currently, automated guidance systems are more prevalent than autonomous systems. Companies such as Trimble have developed systems that can be retrofitted to equipment already owned by farmers. One of the leading systems on the market is the Trimble AgGPS Autopilot. This control system ensures accurate row following with minimal input from the driver (Trimble, 2004a). For most accurate control this system uses Real-Time Kinematic GPS (RTK-GPS) receivers. The AgGPS 214 receiver is an RTK receiver and can provide centimeter level accuracy (Trimble, 2004b). Unfortunately, the cost of this system is extremely high. In addition to the rover receiver and antenna, a base station receiver and antenna as well as two radios for communication between the two receivers must be purchased. The cost, which does not include the controller and necessary hardware, is already in excess of $38,000. Though RTK guidance provides excellent results, the high cost associated with it can make it financially unavailable for farmers with smaller budgets.

A slightly less expensive GPS system commercially available is the OmniSTAR-HP System. The OmniSTAR-HP system utilizes a combination of several reference stations across the world in order to correct errors and compute locations. For North America, there are eleven reference stations and a Network Control Center in Houston, Texas (NovAtel, 2002). The position of remote receivers is determined based on the relationship between receivers, the reference stations, satellites, and the control center which performs corrections for each of the reference stations. Decimeter level accuracy can be achieved with the OmniSTAR-HP system.
The estimated equipment cost of the system is $8,000 plus an additional $800 per year subscription fee.

Also available to the public is the Wide Area Augmentation System (WAAS). WAAS was developed by the Federal Aviation Administration (FAA) to improve position information for aviation use in the United States. The system relies on the use of 25 ground reference stations, two master control stations, and one of two geo-stationary satellites which broadcast a signal on the GPS band (Trimble, 2001). It is not technically a GPS signal but can be received by GPS receivers and antennas that are WAAS enabled (Wells and Pocknee, 2002). The reference stations receive signals from GPS satellites. The master stations monitor the data from the reference stations and create a correction message which is transmitted to one of two geo-stationary satellites (Garmin, 2004). Because the WAAS signal is transmitted free of charge to the consumer, the only purchase necessary for the farmer is the receiver. The price of a compatible receiver is under $3500.

This project sought to achieve two main objectives. The first objective was to develop an autonomously guided vehicle. The development platform used for the autonomous vehicle was an articulated steer tractor. The control approach used GPS data for position information in combination with the pure pursuit, lookahead method described by Amidi (1990).

Due to the high costs associated with RTK auto-guidance systems, the second objective was to analyze the capabilities of different GPS systems on the control of an autonomous vehicle to determine the difference in accuracy between the RTK system and 2 less expensive GPS systems. The analysis of all of the systems was based on positional error with respect to a predefined path.
REFERENCES


CHAPTER 2

EVALUATION OF A PURE PURSUIT SYSTEM ARCHITECTURE

FOR AN AUTONOMOUS, ARTICULATED-STEER VEHICLE

ABSTRACT. Automatic Guidance is an area of research that is especially important in precision agriculture. The technology allows farmers to maximize their resources and at the same time minimize the time required to complete tasks. This paper focuses on the development of an autonomous vehicle. The method of position information is Global Positioning Systems (GPS) data. The programming language used was LabVIEW, Version 6.1. The control approach was a pure pursuit or goal seeking method. The vehicle was tested on several different paths including straight, sinusoidal and abrupt changes in direction. In addition, several speeds were used as well as different turning rates. The results show that the control architecture is a good basis for future research, but requires some improvements.

INTRODUCTION

Autonomous and automated guidance is an area of research that has applications in numerous industries, such as agriculture and manufacturing. Autonomous guidance has the potential to provide advances and advantages that will improve current work practices and profits. For example, one study has shown that the use of automated guidance systems for agricultural applications increased productivity by 3 to 5 percent solely from the reduction of overlap (Naegely, 2001). In each case, the ultimate goal is to have intelligent machines or robots achieve desired tasks without human assistance.

The level of accuracy required to perform a specific task determines the type of system architecture needed. For instance, automated guidance systems such as the Trimble AutoPilot, allow farmers to follow crop rows extremely accurately (Trimble, 2004). However, with this type of system a driver is required to turn the vehicle around at the end of each row. This system bases its corrections on GPS coordinate information.

Other systems have been developed that use mechanical sensors to control the tractor path. Two such systems were developed by Upchurch et al. (1983) and Yekutieli and Pegna (2002). The guidance system developed by Upchurch et al. was designed for an orchard picker and used mechanical sensors to determine the tree’s position with respect to the machine’s centerline. Yekutieli and Pegna developed a control system for vineyard applications where the control algorithm made corrections based on the relationship between mechanical sensors and guide wires positioned above posts within the vineyard. Other systems being studied use vision guidance or laser positioning.
This paper focuses on the initial design of a GPS-based guidance system for an articulated steer vehicle. The requirements for this design do not include integration of safety and inertial sensors. The system uses GPS data to determine position as well as to determine the vehicle’s heading. The control method combines approaches by Martinez et al. (2002) and Amidi (1990). Martinez et al. showed that when developing a control system for a vehicle that is pulling a trailer, it is best to consider the two objects as separate pieces with an angular relationship. The heading of the vehicle is based on the forward-most object’s relationship with the coordinate system in use. An articulated-steer tractor is essentially the same, in that it has two halves that rotate about a central point. The “Pure Pursuit” approach presented by Amidi was shown to be a very accurate path following strategy with an extremely basic algorithm as the foundation. This is a goal-seeking approach, meaning that the control program is constantly adjusting to achieve a point located in front of the tractor’s current position.

METHODS AND MATERIALS

Test Vehicle:

The vehicle used was an articulated steer tractor, Model No.3420-Gc that is manufactured by West Texas Lee Co. (Idalou, TX). The tractor is powered by a 14.9 kW Kohler engine (Kohler Co., Kohler, WI) and motion is delivered by a hydrostatic drive. The hydraulic pump used was an OILGEAR (The Oilgear Company, Milwaukee, WI) Type PVW Variable Delivery Hydrostatic Pump. It is a combination fixed pump and variable rate radial-piston pump with swash plate control supplying fluid to the hydraulic cylinders and motors respectively. The hydraulic motors are Danfoss (Sauer Danfoss Inc., Ames, IA) Geroler and deliver 315 cc/rev. The swash plate and throttle control are activated with an electrical linear actuator. Steering is
controlled by an electrically actuated hydraulic solenoid valve. Depending on the desired direction, the valve supplies pressure to two hydraulic cylinders attached to both halves of the vehicle. When turning left, the left cylinder retracts and the right extends. Right turns are executed in the opposite manner. Electrical signals control all steering operation, which is on-off.

Figure 2.1: Test vehicle.

Wheel Base = 216 cm

$\alpha =$ articulation angle
$\theta =$ Heading angle

Figure 2.2: Overhead depiction of test vehicle with wheelbase dimensions.

In conjunction with the actuators mentioned above, the vehicle has several sensors to provide the vehicle status. A potentiometer is mounted on the articulation point of the tractor to
provide information regarding the angle of articulation. There are also sensors that provide information on the drive pressure and turning pressure for the tractor’s hydraulic system. All sensors and actuators are connected to a LabJack (LabJack Corporation, Lakewood, CO) data acquisition board. The data acquisition board has 8 12-bit analog inputs, 2 analog outputs and the possibility of 20 Digital I/O ports when using the expansion board. The information transfer rate is 50 Hz. It is linked to the control computer through a USB connection. The control computer is a Dell Latitude D600 laptop, Model No. PP05L. It has a Pentium M processor (1.7 GHz, 1 GB RAM) and runs on the Microsoft XP Professional operating system. Position data is obtained through the use of a Trimble (Trimble Navigation Ltd., Sunnyvale, CA) AgGPS 214 RTK-GPS receiver, which relays GPS data to the computer through an RS-232 serial connection. Data is output at a rate of 5 Hz. The receiver’s antenna is mounted on top of the cab in the forward most position of the tractor and along the centerline.

**Figure 2.3:** Basic components of system architecture.
Control Algorithm:

The control scheme used for this project assumed a kinematic model of all components. Variations that result from the dynamic characteristics of the mechanical, hydraulic, and electrical systems were considered negligible. The control program was written in LabVIEW, Version 6.1, developed by National Instruments Corporation (Austin, TX). Another LabVIEW program linked to the control program was developed to read data strings from the GPS receiver and convert the data to usable information. Flow charts detailing the programs and the sub-programs contained within each program can be found in Appendices B and C. This additional program also determines the heading of the vehicle based on calculations made from current and previously recorded GPS coordinates as well as monitoring the status of all of the vehicle’s sensors and actuators. The GPS Read program is a 2 sequence program. The Control program is a 7 sequence program.

The control architecture is based on the pure pursuit method used by Amidi (1990), which is a goal seeking algorithm. Based on a predetermined lookahead distance, the control algorithm computes the appropriate turning radius to achieve the desired look ahead coordinate. The relationship is very simple and represented by Equation 2.1 and Figure 2.4:

\[ R = \frac{L^2}{2x} \]

where,

- \( R \) = turning radius,
- \( L \) = absolute distance between current and lookahead coordinates, and
- \( x \) = relative x distance between current and lookahead coordinates.
Figure 2.4: Description of Control Equation Relationship.

As opposed to the vision system Amidi used to determine the lookahead coordinates, the control algorithm developed for this project uses an input map with pre-defined geo-spatial coordinates. By reading the current GPS coordinate and corresponding heading, the algorithm determines the future heading and the appropriate coordinate from the input map and calculates the turning radius required to achieve the lookahead coordinate. Please reference the flow diagrams for Lookahead Determiner.Vi, Current Heading.Vi, and Future Heading.Vi in Appendix C for descriptions of these processes.

After computing the desired radius, the value is converted to the corresponding voltage value required at the articulation potentiometer. The relationship between voltage and radius is an inverse linear relationship. It is presented in Equation 2.2 and Figure 2.5:
\[ \beta = \psi \times V + C \]

where,

\( \beta \) = inverse of radius,
\( \psi \) = slope in units of \((\text{deg/m})/\text{volt}\),
\( V \) = voltage at articulation potentiometer, and
\( C \) = intercept in units of \((\text{deg/m})\).

**Figure 2.5:** Representation of Voltage and Radius Relationship

After computing the desired voltage, the algorithm then compares the desired voltage to the current voltage. The difference in voltage is multiplied by the turning pulse rate to determine the correct pulse duration to be applied to the relay responsible for steering. The full turning pulse rate, 1.66 sec/V, was determined experimentally by Stuart Pocknee (S. Pocknee, personal communication, 7 April 2004). The pulse rate was determined by recording the amount of time required to produce a 1 volt change in the reading of the articulation potentiometer. Corrections are made repeatedly until the vehicle’s position is within the specified range (3 m) of the lookahead coordinate. Once the vehicle’s position is within the specified range, a new lookahead
coordinate is determined. The process repeats until the vehicle reaches the end of the input path. The steps described above are represented by the flow charts of Sequences 3-6 (Reference Appendices B-6 to B-10). The same basic process is repeated in each of the sequences.

Testing Procedure:

Evaluation of the control algorithm accuracy was based on the ability of the vehicle to follow five separate paths. To develop the different paths, two initial GPS coordinates were recorded, the distance between them being approximately 47 m. The two GPS coordinates were converted to UTM coordinates in accordance with UTM Zone 17. Using the two UTM coordinates and Microsoft EXCEL, five different paths were developed. The distance between the RTK base station receiver and rover receiver was approximately 0.39 km. The first path was a straight line. The second path was a straight line with a 90° right hand turn at the midpoint of the original straight line path. The remaining paths were sinusoidal. The amplitudes and wavelengths were based on the minimum turning radius of the vehicle, which is approximately 2.74 m. In all cases, the amplitude was 3.5 m, which was slightly more than the minimum turning radius. The wavelengths were multiples of 7 m, the diameter of a circle of minimum turning radius. The paths used were as follows:

**Path 1:** Straight Line.
**Path 2:** Amplitude 3.5 m, Wavelength 56 m.
**Path 3:** Amplitude 3.5 m, Wavelength 42 m.
**Path 4:** Amplitude 3.5 m, Wavelength 28 m.
**Path 5:** Straight with 90 Degree Turn.

In addition to the evaluation based on path following, speed and turning pulse rate were varied. For each path, three different turning pulse rates were examined: full, half, and quarter. Because the vehicle has on-off turning controls, the half and quarter pulses were used as a
pseudo-proportional control. Essentially, the half and quarter pulses were put in place to
determine if shorter pulse durations would be a better alternative when minimal changes in
direction were required. The speeds used were ~2.4 km/h, 5.0 km/h, and 7.5 km/h. Each path
was run 5 times with each speed and turning pulse rate combination.

Program Evaluation:

Error for each run was calculated by determining the perpendicular distance from the
input map to the logged data points. To simplify the calculations, all maps were converted from
the original north easterly direction to a northern direction. As stated previously, all data points
were recorded using the Trimble AgGPS 214 receiver in conjunction with the RTK-GPS system.
For the sinusoidal paths, only the straighter portions of each path were considered. After
computing all of the errors associated with each path, a mean error and 95% confidence interval
were developed for each speed and turning duration, control combination. These two statistics
were then used to make a determination about the accuracy of each control combination.
Figure 2.6: Mean error and 95% confidence interval for all pulse rate combinations. Speed is approximately 2.4 km/h.

The actual path data is found in Figures 2.9-2.25. Figure 2.6 helps to identify which pulse rates worked best in different situations. The Full Pulse rate and Half Pulse rate produced very similar results for Paths 1 and 2, having errors under 10 cm. As the required turning radius in the path was decreased (paths became more curved) the error started to increase. Additionally, the rate of increase in error was much greater for the Half Pulse than for the Full Pulse (Figure 2.6). The Quarter Pulse rate (Figure 2.6), only appeared to work well in Path 2. In this instance the error was in line with the Full and Half Pulses. In all other cases the mean error was in excess of 40 cm.
The results from Path 5 are in the last column of data in Figures 2.6. It is very clear from this data that the control system does not handle extremely abrupt changes in direction well. The mean error is large, regardless of the pulse rate.

Due to the nature of the turn in Path 5, it can be considered a step input. Further analysis was performed to determine if there is a clear relationship between vehicle characteristics and the maximum perpendicular deviation from the right-hand turn portion of Path 5 (column 6, Table 2.1). Table 2.1 compares maximum deviation of each run combination to the distance between the vehicle and the last point of the original path at the first instance where the lookahead coordinate falls on the right-hand turn portion of the path. Table 2.1 also provides heading difference information for the current location and look-ahead point at the same instance. No conclusive explanation can be made as to why the vehicle is unable to achieve abrupt turning. There is no direct correlation between angular difference and deviation or distance and deviation. Runs 3 and 5 of the Half Pulse turning rate combination have similar angular differences (29° and 23°) and distances (5.3 and 5.5 m) yet produce maximum deviations of 3.4 and 1.1 m respectively. The same argument can be made for runs 1 and 2 of the Full Pulse turning rate combination. Figures 2.21-2.23 show the data for these runs.
Figure 2.7: Relationships for tractor with respect to Path 5. Corresponds to data in Table 2.1.

Table 2.1: Data comparison for each pulse rate using Path 5 as the input map. Comparisons show distance from end of original straight path to tractor position and angular difference between current heading and desired heading for first lookahead point on right hand turn portion of the input map. These values are then coupled with the maximum perpendicular deviation of the tractor from the right hand turn portion of the input map.

<table>
<thead>
<tr>
<th>Pulse</th>
<th>Run</th>
<th>Abs. Dist. (m)</th>
<th>Latitude Dist. (m)</th>
<th>Angular Difference (Deg.)</th>
<th>Max Deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarter</td>
<td>1</td>
<td>4.354</td>
<td>4.345</td>
<td>47.343</td>
<td>4.199</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.902</td>
<td>5.902</td>
<td>24.044</td>
<td>4.132</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.522</td>
<td>5.484</td>
<td>16.143</td>
<td>5.755</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.894</td>
<td>2.867</td>
<td>69.145</td>
<td>7.699</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.209</td>
<td>6.202</td>
<td>-1.979</td>
<td>5.741</td>
</tr>
<tr>
<td>Half</td>
<td>1</td>
<td>3.980</td>
<td>3.979</td>
<td>52.602</td>
<td>0.480</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.336</td>
<td>3.335</td>
<td>58.121</td>
<td>0.529</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5.308</td>
<td>5.307</td>
<td>29.099</td>
<td>3.397</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.494</td>
<td>4.493</td>
<td>47.582</td>
<td>3.351</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5.510</td>
<td>5.510</td>
<td>22.663</td>
<td>1.097</td>
</tr>
<tr>
<td>Full</td>
<td>1</td>
<td>3.811</td>
<td>3.811</td>
<td>55.883</td>
<td>0.251</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.455</td>
<td>3.452</td>
<td>56.291</td>
<td>3.187</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.907</td>
<td>4.906</td>
<td>34.379</td>
<td>0.063</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.270</td>
<td>5.263</td>
<td>42.167</td>
<td>4.388</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.276</td>
<td>6.274</td>
<td>-0.343</td>
<td>2.176</td>
</tr>
</tbody>
</table>

When the speed was increased from 2.4 km/h to approximately 5 km/h the control program was unable to produce accurate results. The vehicle repeatedly strayed from the...
intended path. Paths 1 and 2 were run first. Because the vehicle could not accurately follow either of the paths, the rest of the trial runs were aborted. It was deemed unnecessary to attempt the more difficult turning paths when it was realized that the vehicle could not handle the straighter paths. After finding that the middle speed could not be controlled by the computer algorithm, the high speed was not attempted.

Table 2.2 shows some example data from an attempt to follow Path 1 at 5 km/hr and Full pulse rate. The data corresponds to Figure 2.24. By reviewing Figure 2.24 and Table 2.2, it was noticed that the slow update rate of the control program could not produce adjustments quickly enough to achieve the desired heading values. Once the vehicle began to vary slightly from the path it was unable to correct its motion and continue in the original direction.

**Table 2.2:** Example data from Path 1 with speed setting of 5 km/h and Full Pulse rate.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Dist. (m)</th>
<th>Current Coordinate (UTM)</th>
<th>Lookahead Coordinate (UTM)</th>
<th>Current Heading (Degrees)</th>
<th>Desired Heading (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>6.2</td>
<td>3485294.3</td>
<td>259537.5</td>
<td>3485299.5</td>
<td>259540.9</td>
</tr>
<tr>
<td>3.7</td>
<td>4.2</td>
<td>3485295.4</td>
<td>259540.4</td>
<td>3485299.5</td>
<td>259540.9</td>
</tr>
<tr>
<td>3.6</td>
<td>3.9</td>
<td>3485296.6</td>
<td>259543.5</td>
<td>3485299.5</td>
<td>259540.9</td>
</tr>
<tr>
<td>2.1</td>
<td>3.5</td>
<td>3485298.1</td>
<td>259544.1</td>
<td>3485299.5</td>
<td>259540.9</td>
</tr>
</tbody>
</table>

When moving slowly, Table 2.3 shows that an update of position occurs every 2 m on average. When speed is increased (5 km/h), position updates only occur every 4.1 m. As speed rises, a much greater distance is covered in the same amount of time. If traveling straight, the problem is negligible, but when turning is required, more error is intrinsic. Slight errors in turning result in a greater displacement of the vehicles position before the next correction is made. Figure 2.8 helps to demonstrate the problem.
Table 2.3: Difference in distance covered using average time from Table 2.2 and Speeds 1 and 2.

<table>
<thead>
<tr>
<th>Average Update (s)</th>
<th>Dist. (m) @ 2.4 km/h</th>
<th>Dist. (m) @ 5 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>2.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Figure 2.8: Demonstration of problems that occur by calculating heading from GPS data when speed of vehicle is too fast for the control algorithm.

Some additional issues are the methods used to calculate heading and lookahead coordinates. Though the GPS receiver outputs data at a rate of 5 Hz, the GPS Read program outputs new coordinate and heading values at a slower rate of 2.5 Hz. The heading calculations for the tractor are based on current and old position values. The result, especially in cases of tight turning, can be a large angular difference in actual and calculated heading values. A way to alleviate this problem would be to use a compass in place of the calculations from GPS coordinates. The compass would provide more accurate data by giving relatively exact heading values at the time of need, independent of previous positions.

Having the lookahead distance set to a constant value (6 m) limits the points that can be used by the vehicle. A place where the problem is especially evident is the need for tight turning...
radii required by some of the sinusoidal paths. The tighter the turning radius becomes, the more points the control program will overlook before it finds one within range. This can lead to clipping of some turns.

CONCLUSIONS

Based on the results obtained from the series of tests performed on the control architecture, several observations can be made about the abilities and deficiencies of the control system. First, Figure 2.6 shows that the control architecture can produce accurate path following using the combination of a goal seeking approach and the use of GPS data for position information. The results also show that the use of half the full pulse rate worked well for the straight paths as was previously believed. The quarter pulse rate, which was thought to have possible benefits in situations of minimum change in direction, did not work well. In general, the only advantage to using the half pulse rate is that it will produce less overshoot and lower frequency oscillation. Using the full pulse rate produces quicker adjustments in vehicle geometry, but can result in overshoot and high frequency oscillation. As is obvious from the results for increased speed, the control architecture needs improvement. Possible causes of the problem are slow data acquisition and the operating speed of the hardware. Running on a non-embedded operating system prevents the control of what processes are in use on the computer. Due to this factor the program was not able to process information quickly enough to implement control decisions. This is a problem that must be tackled in future research. The way in which the goal seeking approach was implemented is also believed to be a contributing factor. After determining the look-ahead coordinate, the vehicle makes adjustments to reach that point until it is within a certain distance of that point. The data showed that this method worked well at low
speed. Amidi’s approach, however, determined a new lookahead coordinate after each adjustment. It is believed that making this change could improve the ability of the control architecture to accurately follow a path at higher speeds.

Overall, the method chosen is believed to be a good foundation for an autonomous vehicle. Improvements for future development include: (1) the use of an embedded processing system or a processing system that limits background processes, (2) the control architecture would benefit from a variable look-ahead distance based upon the speed of the vehicle and required turning radius, automatically adjusting while the vehicle is in motion, (3) the vehicle should be equipped with a compass to determine heading as opposed to determining heading based upon calculations made from subsequent GPS coordinates, and (4) before the vehicle could be released as a viable autonomous system, safety controls should be implemented.
REFERENCES


Figure 2.9: Data points for Path 1 at Full Pulse rate and Speed 1.

Figure 2.10: Data points for Path 1 at Half Pulse rate and Speed 1.
**Figure 2.11:** Data points for Path 1 at Quarter Pulse rate and Speed 1.

**Figure 2.12:** Data points for Path 2 at Full Pulse rate and Speed 1.
Figure 2.13: Data points for Path 2 at Half Pulse rate and Speed 1.

Figure 2.14: Data points for Path 2 at Quarter Pulse rate and Speed 1.
Figure 2.15: Data points for Path 3 at Full Pulse rate and Speed 1.

Figure 2.16: Data points for Path 3 at Half Pulse rate and Speed 1.
Figure 2.17: Data points for Path 3 at Quarter Pulse rate and Speed 1.

Figure 2.18: Data points for Path 4 at Full Pulse rate and Speed 1.
**Figure 2.19:** Data points for Path 4 at Half Pulse rate and Speed 1.

**Figure 2.20:** Data points for Path 4 at Quarter Pulse rate and Speed 1.
Figure 2.21: Data points for Path 5 at Full Pulse rate and Speed 1.

Figure 2.22: Data points for Path 5 at Half Pulse rate and Speed 1.
Figure 2.23: Data points for Path 5 at Quarter Pulse rate and Speed 1.

Figure 2.24: Data points for Path 1 at Full Pulse rate and Speed 2.
Figure 2.25: Data points for Path 2 at Full Pulse rate and Speed 2.
CHAPTER 3

DYNAMIC ANALYSIS OF THREE GPS SYSTEMS OF VARYING ACCURACY

ON THE CONTROL OF AN AUTONOMOUS VEHICLE

\(^1\)

ABSTRACT. Global Positioning Systems (GPS) are widely used in the realm of precision agriculture for a multitude of different tasks. This paper focuses on the testing of three GPS receivers and GPS systems of varying accuracy and cost used to control an autonomous tractor. Each receiver was used on a combination of different paths to determine how accurately each enabled path following. There were five different paths, including straight and sinusoidal. Each receiver was used for five passes on each of the five paths. The three systems were the Trimble RTK, OmniSTAR-HP, and WAAS. The RTK performed the best but the OmniSTAR-HP proved adequate for certain non-row crop applications.

KEYWORDS. GPS, RTK, OmniSTAR-HP, WAAS, Autonomous control, Precision Agriculture.
INTRODUCTION

Precision agriculture is an agricultural production strategy that attempts to site-specifically manage variability within farming systems. One area of investigation is the study of automated guidance and autonomous guidance of agricultural vehicles. Automatic guidance systems allow farmers to increase productivity by allowing them to prevent errors related to overlap and gapping. According to one source, automatic guidance systems have helped to increase productivity by 3 to 5 percent solely from reduction of overlap (Naegely, 2001). In addition to the overlap reduction, Gan-Mor and Clark (2001) suggest that the use of automatic guidance systems can help to reduce problems such as soil erosion, hard pan development and yield reduction that result from the use of heavy machinery. Automatic guidance systems limit these problems by minimizing the amount of ground area in contact with agricultural equipment.

With autonomous vehicles, methods that will provide the most accurate indication of vehicle and/or implement position are being investigated. Reasons for this include concerns with safety, potential crop damage, and production. The level of accuracy needed will depend on the application. Some situations, such as spraying chemicals on a field, only require 30-50 cm accuracy. The most accurate GPS position systems are based on Real-Time Kinematic GPS (RTK-GPS). Although RTK-GPS systems provide great accuracy, often within 1cm, the systems are very expensive. In addition, the RTK-GPS systems require a base station receiver and radio transmitters in order to perform real-time corrections. The need for a base station and the cost are limiting factors of the RTK-GPS system. This paper proposes that 3 different GPS systems be compared to determine if there is a reasonable difference between the RTK system and less expensive and slightly less accurate GPS systems when used as a source of position...
information for autonomous control of an articulated vehicle. The three types of GPS systems used were Trimble AgGPS 214 RTK-GPS, NovAtel Pro-Pak LB with OmniSTAR-HP prescription differential correction, and the Trimble Ag132 with WAAS differential correction.

**Differential GPS:**

All of the systems tested use differential GPS. Differential GPS helps to alleviate many of the errors associated with GPS data, including atmospheric signal errors, satellite and clock errors, multi-pathing, etc. (NovAtel, 2002a). The reduction in errors is accomplished by communicating signals between the GPS satellites and a reference station of known location. The reference station may be a base station, a satellite differential service provider, or radio-beacon (Trimble, 2004a). Receiver location is then calculated from the corrections of the reference station (Dana, 2000). While this system eliminates error, it is not absolute. The farther the remote receiver is from the reference station, the larger the error becomes.

**RTK-GPS:**

Real Time Kinematic GPS further reduces the errors associated with simple DGPS. RTK systems use two or more receivers, which are the roving remote receiver(s) and a base station receiver. The base station and the remote receiver both communicate with the same satellites in order to estimate the location of the remote receiver (Trimble, 2001). Data is transmitted through radio link and accuracies of the millimeter level are possible (Trimble, 2001).

**OmniSTAR-HP:** The OmniSTAR-HP system uses differential corrections but is not a RTK system. The OmniSTAR-HP system utilizes a combination of several reference stations across the world in order to correct errors and compute locations. For North America, there are eleven reference stations and a Network Control Center in Houston, Texas (NovAtel, 2002b).
position of remote receivers is determined based on the relationship between receivers, the reference stations, satellites, and the control center which performs corrections for each of the reference stations. Decimeter level accuracy can be achieved with the OmniSTAR-HP system (NovAtel, 2002b).

*WAAS:*

The Wide Area Augmentation System (WAAS) was developed by the Federal Aviation Administration (FAA) to improve position information for aviation use in the United States. The system relies on the use of 25 ground reference stations, two master control stations, and two geo-stationary satellites, which broadcast a signal on the GPS band (Trimble, 2001). It is not technically a GPS signal but can be received by GPS receivers and antennas that are WAAS enabled. The reference stations receive signals from GPS satellites. The master stations monitor the data from the reference stations and then create a correction message which is transmitted to the geo-stationary satellites (Garmin, 2004).

**METHODS AND MATERIALS**

*Test Vehicle:*

The vehicle used was an articulated steer tractor, Model No.3420-Ge that is manufactured by West Texas Lee Co (Idalou, Texas). The tractor is powered by a 14.9 kW Kohler engine (Kohler Co., Kohler, WI) and motion is delivered by a hydrostatic drive. The hydraulic pump used was an OILGEAR (The Oilgear Company, Milwaukee, WI) Type PVW Variable Delivery Hydrostatic Pump. It is a combination fixed pump and variable rate radial-piston pump with swash plate control supply fluid to the hydraulic cylinders and motors respectively. The hydraulic motors are Danfoss (Sauer Danfoss Inc., Ames, IA) Geroler and deliver 315 cc/rev.
The swash plate is activated with an electrical linear actuator, as is the throttle control. Steering is controlled by an electrically actuated hydraulic solenoid valve. Depending on the desired direction, the valve supplies pressure to two hydraulic cylinders attached to both halves of the vehicle. When turning left, the left cylinder retracts and the right extends. Right turns are executed in the opposite manner.

![Test vehicle](image)

**Figure 3.1:** Test vehicle.

The control program for the vehicle was written in LabVIEW, Version 6.1 developed by National Instruments Corporation (Austin, TX). The computer used for control is a Dell Latitude D600 laptop, Model No. PP05L. It has a Microsoft XP operating system and utilizes a Pentium M processor (1.7 GHz, 1 GB RAM). All of the GPS receivers are connected to the control computer through a RS-232 data link, with an update rate of 5 Hz. The sensors on the vehicle, which monitor system pressures, articulation state, throttle settings, etc., and the electrical actuators which control vehicle motion, are linked to the computer through a LabJack (Labjack, Corporation, Lakewood, CO) data acquisition board. The data acquisition board has 8, 12-bit analog inputs, 2 analog outputs and the possibility of 20 Digital I/O ports when using the expansion board. The data transfer rate is 50 Hz. It is linked to the control computer through USB connection. Figure 3.2 provides a reference of the system components.
**Figure 3.2:** Basic components of system architecture.

*GPS Receivers:*

**Trimble AgGPS 214:** The Trimble AgGPS 214 (Trimble Navigation Ltd., Sunnyvale, CA) is a dual frequency RTK-DGPS enabled receiver. It requires the use of a local base station in order to achieve RTK accuracy, which is on the order of 1 cm. The communication between the two receivers is facilitated by the use of Trimble TRIMCOMM 900 data link radios at both the rover and the base station. The firmware used for both the rover and base station receivers was Version 1.45. The estimated price for the total system is $38,000.

**Figure 3.3:** Trimble AgGPS 214 receiver with antenna (Trimble, 2004b).
NovAtel ProPak-LB: The NovAtel (NovAtel Inc., Calgary, Alberta, Canada) ProPak-LB is a dual frequency receiver, which is capable of operating on several different correction systems. The OmniSTAR-HP (OmniSTAR Inc., Houston, TX) satellite subscription service was used for this test. The horizontal accuracy is on the order of 10 cm. Unlike the AgGPS 214, the ProPak-LB requires no base station to be able to perform real time corrections. The firmware used on the ProPak-LB was Version 2.14. The estimated price of the system is $8,000 plus an additional $800 per year subscription fee.

Figure 3.4: NovAtel ProPak-LB receiver (NovAtel, 2003).

Trimble AgGPS 132: The Trimble AgGPS 132 (Trimble Navigation Ltd., Sunnyvale, CA) is a receiver capable of operating with several different correction systems including Coast Guard Beacon and satellite corrections. For the purpose of this study the correction system used was the WAAS. The accuracy level is sub-meter. The firmware used was Version 1.71. The estimated price is $3,495.

Figure 3.5: Trimble AgGPS 132 receiver with antenna (Trimble, 2004c).
**Trimble AgGPS 114:** The Trimble AgGPS 114 (Trimble Navigation Ltd., Sunnyvale, CA) was used to obtain vehicle speed in this study. Speed is obtained by using the VTG NMEA output string.

Each receiver was set to output position data through the GPGGA NMEA string. This data string provides information on position, satellite quality, number of satellites, PDOP, etc. The update rate for each receiver was also set to 5 Hz. Using the latitude and longitude position data from the GPGGA string, the control program converts this information to UTM coordinates. This position data is then compared to a predetermined input map and corrections in the turning angle of the tractor are made in order to follow the path.

![Trimble 114 receiver / antenna](image)

**Figure 3.6:** Trimble 114 receiver / antenna (Trimble, 2004d).

**Testing Procedure for GPS Analysis:**

**MAPS:**

All of the maps used in this study were located in the gravel parking lot in front of the NESPAL building on the Tifton Campus of the University of Georgia. Five separate maps were used for testing the relative accuracies of each GPS system. The first map was a straight line path. The straight line path was developed using Microsoft Excel to generate the points joining two recorded GPS points. The 2 end-points were recorded with the Trimble AgGPS 214 receiver
using RTK operation and then converted to UTM coordinates in correspondence with UTM zone 17 before generating the points along the line in Microsoft Excel. The other four maps are sinusoidal paths of equal amplitude but varying wavelength. The paths were developed using the latitudinal points from the straight line path and calculating the longitudinal coordinates according to the Equation 3.1:

$$\text{Long}_x = \text{Long}_1 + 2A \cdot \sin\left\{\frac{\pi \cdot \text{Lat}_x}{\lambda}\right\}$$

where,

- $A = \text{amplitude}$,
- $\lambda = \text{wavelength}$,
- $\text{Long}_1 = \text{longitude coordinate of first point}$,
- $\text{Long}_x = \text{sinusoidal longitude coordinate}$, and
- $\text{Lat}_x = \text{latitude coordinate along straight line}$.

The points of the sinusoidal paths were rotated to align with the original straight line path. The amplitude in each case was 3.5 meters, which is slightly more than the minimum turning radius of the tractor (~ 3 meters). The wavelengths were multiples of 14 m, which is equivalent to twice the diameter of a circle of minimum turning radius for the tractor. The total length of the straight line path was approximately 47 m. The straight line path followed a north easterly direction at an angle of approximately 65 degrees from due east.

**Path 1:** Straight.
**Path 2:** Amplitude 3.5 m; Wavelength 14 m.
**Path 3:** Amplitude 3.5 m; Wavelength 28 m.
**Path 4:** Amplitude 3.5 m; Wavelength 42 m.
**Path 5:** Amplitude 3.5 m; Wavelength 56 m.
Figure 3.7: Test area where test trials were performed.

REPETITIONS:

The vehicle position was recorded for each path a total of five times with each GPS system. The baseline receiver (used to compare to the tested GPS receivers) for every test, was the AgGPS 214 receiver. The testing was performed over a 3 day period. Each day all five paths were run with one GPS system while recording time and weather conditions. The other two GPS systems were run on the following days at approximately the same time of day. Two LabVIEW computer programs were written to control the vehicles path. The first program was written to obtain GPS and vehicle sensor data (Reference Appendix A, GPS Program). The second program (Appendix A, Control Program) used the coordinate information from the GPS Program to determine the appropriate course of action required to accurately direct the tractor’s motion. The tested GPS and the Baseline GPS latitude and longitude coordinates were recorded into a computer file. The coordinates from the RTK system were recorded using the program FarmSiteMate, developed by FarmWorks Software (Hamilton, Indiana) and a pocket PC (Ipaq
The same approach was used to record vehicle speed from the AgGPS 114 receiver.

For each run, the starting positions were marked by flags and the tractor was started from the same position, (path dependent) to ensure test repeatability. For each tested receiver, the order of paths was 2, 3, 4, 5, 1. This method was employed to make sure that similar paths were run at approximately the same time each day. Ehsani et al. (2002) discussed the environmental errors that can occur with GPS. Due to this error, Ehsani et al. suggested that the ideal situation for comparing different GPS systems is to ensure that testing be completed within the same timeframe. The starting time for the tests was approximately 2:25 p.m. EST. The time required to run each set of tests was 2 to 2 ½ hours.

**GPS Evaluation:**

The ability of each GPS system to control the articulated vehicle for each test path was evaluated by comparison of position data recorded from the baseline receiver. All of the recorded data, including the input paths, were transformed such that the direction of travel was South to North. To analyze the coordinate data, the perpendicular distance between data points from the different runs of each GPS receiver and the map paths followed were compared. Comparisons were only performed along the straighter portions of each map path. The curves resulting in change in direction were not considered. A LabVIEW program was written to calculate the perpendicular error between the recorded data and path for each GPS system. The 95% confidence intervals and mean error of each GPS system, calculated in Microsoft Excel, were compared to the paths they were set to follow.
RESULTS

Evaluations were made based on longitudinal variations after transformation of the data from the original direction to South-North direction. The data did show certain trends that are notable. The most significant of which was the error in data recorded with the OmniSTAR-HP and RTK system. As mentioned previously the OmniSTAR-HP and RTK systems have a reported accuracy of approximately 10 and 1 cm, respectively.

Figures 3.9-3.13 show each of the five map paths and the average path produced by each of the different GPS systems. The average paths were developed by selecting data points from Runs 1-5 of each system that had corresponding latitude values. A LabVIEW program was written to select the appropriate points from each run.

![Bar Chart: Mean Error and +/- 95% Confidence Interval for Paths 1-5 With OmniSTAR-HP and RTK System Used as Control.]

**Figure 3.8:** Mean Error and +/- 95% Confidence Interval for Paths 1-5 With OmniSTAR-HP and RTK System Used as Control.
Figure 3.8 shows that though the OmniSTAR-HP trials were consistent in terms of low variability, the position error with respect to the input map was high. At no point was the mean error less than 40 cm. In most cases the mean error was greater than 80 cm. The RTK system, on the other hand, in no case had a mean error of more than 22 cm. For path 1 (Straight ahead), the mean error of the OmniSTAR-HP was approximately 6.2 times greater than the RTK system. Both systems exhibited the lowest mean error in this case. The highest mean error was exhibited for path 2 (wavelength – 14 m) The OmniSTAR-HP had a mean error around 6.7 times higher than the RTK system in this case. The OmniSTAR-HP system also appeared to produce an offset from the input path which is very evident in Figures 3.10 and 3.11.

Another important result to consider is the clipping that appears in the turning data for the RTK and OmniSTAR-HP systems. This clipping is a result of the lookahead determination in the control algorithm and is not due to the position data provided by the different GPS systems. The data also shows that the errors for the RTK and OmniSTAR-HP systems are much greater than the respective advertised errors for each. In the best case for each system (Path 1), the RTK data had an error 7 times greater than advertised and OmniSTAR-HP error was 4 times greater than advertised. This error is most likely influenced by the control algorithm, not solely the abilities of the GPS systems.

An additional trend which was noticed with both the OmniSTAR HP system and the RTK system, was the decreasing accuracy that resulted when more abrupt changes in direction of travel were required (Figures 3.8) It is obvious in Figure 3.8 that errors in the OmniSTAR-HP increase almost linearly with the increase in turn frequency. This trend is repeated in the RTK data, except that the mean error for path 5 suddenly increases. Figure 3.13 does not show this
increase in error because it is a representation of the average path produced by the vehicle. Run 5 of this data set had a slight amount of oscillation at the beginning which accounts for the discrepancy in error.

The data from the WAAS system was too erratic to make a definitive determination of its characteristics. In some instances, the WAAS system appeared to perform well. This is evidenced in Figures 3.10 and 3.13. In both of these cases the path produced by the articulated vehicle followed the shape of the map well. At other times the data points vary greatly. Often, when the WAAS system was used for control, the tractor would become lost and begin circling to try to obtain points. When this occurred, the run was terminated. The WAAS data in Figures 3.9-3.13 may appear to be more consistent than it actually is due to this factor.

![Map Straigh RTK Omni WAAS](image)

**Figure 3.9:** Mean positions for all GPS systems, Path 1.
Figure 3.10: Mean positions for all GPS systems, Path 2.

Figure 3.11: Mean positions for all GPS systems, Path 3.
**Figure 3.12:** Mean positions for all GPS systems, Path 4.

**Figure 3.13:** Mean positions for all GPS systems, Path 5.
CONCLUSIONS

Based on the figures above, several conclusions can be made. The first, as expected, is that the RTK system was the most accurate in every case. The OmniSTAR-HP system matched the map path well in each case, but mean error was never less than 40 cm. This is unacceptable for guidance applications that require high accuracy such as planting of row crops. It was stated in the results that this error is most likely exaggerated as is the RTK error due to inadequacies of the control program. Regardless of this fact, the data showed that the OmniSTAR-HP system produced a considerable shift from the input path. This shift would be present even with a more refined control program. As to the cause of the shift, only speculative answers can be given. It is believed to be inherent to the OmniSTAR-HP system and not environmental conditions as it was noticed in testing on separate days from the official test. After speaking with Stuart Pocknee, he suggested that the OmniSTAR-HP may have a considerable time delay between the output of the position data and the actual position (S. Pocknee, personal communication, May 2004). Due to this factor it is believed that the error produced with OmniSTAR-HP would result in a significant destruction of row crops. Gan-Mor and Clark (2001) state that error in “simple applications such as tillage or chemical applications for non-row crops can be reduced by low-cost guidance systems.” Given the error data and accurate path shapes recorded in this experiment, it is believed that the OmniSTAR-HP is capable of performing in the situations described by Gan-Mor and Clark, but is not an acceptable substitute for RTK-GPS in tasks requiring high accuracy.

The WAAS system behaved much better than expected, but is not acceptable for guidance of any sort using the control algorithms employed. During several runs, the WAAS
error was so large that the articulated vehicle would begin turning erratically. The vehicle deviated so far from the path that the runs were terminated.
REFERENCES

Dana, P. H. 2000. The Global Positioning System. Available at:


Gan-Mor, S. and R.L. Clark. 2001. DGPS-Based Automatic Guidance-Implementation and


NovAtel. 2002a. GPS system errors. In OEM4 Family of Receivers Installation & Operation


Part No.: 40868-01-ENG. Revision: A. 1-5.

Trimble, 2004a. GPS for Precision Agriculture. Available at:

30 April 2004.

26 April 2004.

26 April 2004.
CONCLUSIONS

Any advances achieved through work in precision agriculture ultimately result in benefits to farmers. This study compared three different GPS systems on the control of an autonomous-articulated vehicle. The control approach used for the vehicle was a simplistic “Pure Pursuit” or goal seeking method that uses a lookahead distance to determine direction and heading. The vehicle did not employ any concerns for safety or roll control adjustment, as the intention was to develop the foundation of an autonomous architecture that will be used for future research. Using the Trimble RTK-GPS the control architecture was shown to produce good results for path following at slow speeds (~2.4 km/h). However, increasing speed to approximately 5 km/h caused uncontrollable error in path following. This error is believed to have been derived from the preset lookahead distance that is constant regardless of speed. Adjusting the lookahead technique to account for speed would most likely solve this problem.

The study of the three different GPS systems including OmniSTAR-HP and WAAS in addition to the Trimble RTK-GPS helped to determine the abilities of the different systems for control situations. As was thought initially, the RTK-GPS provided the most accurate results for guidance, never producing mean errors of more than 0.2 m. The OmniSTAR-HP system followed the paths well with respect the shape of the path. The mean error though was never less than 0.4 m. The WAAS could not produce accurate paths to any extent.

Some of the error noticed with the different systems is inherently caused by deficiencies in the control program. Considering this fact, it is still believed that the OmniSTAR-HP system
would not produce accurate enough results for guidance in cases that require high accuracy such as row crop applications. I do believe that it would be a good low cost alternative for guidance where high accuracy is not needed such as chemical application for non-row crops.
APPENDIX A: USER INTERFACES FOR CONTROL PROGRAMS
APPENDIX A-1: FRONT PANEL OF TRACTOR CONTROL PROGRAM DEVELOPED IN LABVIEW, VERSION 6.1
APPENDIX A-2: FRONT PANEL OF PROGRAM TO GATHER GPS AND SENSOR DATA, DEVELOPED IN LABVIEW, VERSION 6.1
APPENDIX B: FLOW DIAGRAMS FOR CONTROL PROGRAMS
APPENDIX B-1: FLOW DIAGRAM OF TRACTOR CONTROL ALGORITHM

Loop1

Run Value

Run Status? True

Sequence Structure (0-7)

Run Status? False

Loop2

Grab Sensor Data, Coordinate Data, and Heading Data
APPENDIX B-2: SEQUENCE STRUCTURE FOR TRACTOR CONTROL ALGORITHM

Start

Seq. 0
Read Input Map
Initialize Values
Determine Last Coordinate

Seq. 1
Set Throttle

Seq. 2
Determine Initial Heading

Seq. 3
Set Initial Articulation Angle

Seq. 4
Set In Motion

Seq. 5
Adjust to Achieve
First Map Coordinate

Seq. 6 (A & B)
Adjust to Achieve Path Following

Seq. 7
Stop Motion
Lower Throttle
Output Data to File

End
APPENDIX B-3: SEQUENCE 0

Start

Grab Desired Input Map

MapRead.Vi

Determine First Map Coordinate

Go to Sequence 1
APPENDIX B-4: SEQUENCE 1

Start

Throttle Control.Vi

Wait

Go to Sequence 2
APPENDIX B-6: SEQUENCE 3

Start

Grab Current Heading
Grab Current Latitude & Longitude
Grab First Map Coordinate

Future Heading.Vi
Calculate Distance to Point

Calculate Desired Turning Radius
Grab Initial Heading
Radius Factor.Vi

Grab Current Voltage
Convert to Voltage

Determine Pulse Length

Current > Desired

Pulse Left for Calculated Time
Pulse Right for Calculated Time

Go to Sequence 4
Store Values inArray
APPENDIX B-7: SEQUENCE 4

Start

Grab Pulse
Length & Direction

Begin Motion

Wait

Go to
Sequence 5
APPENDIX B-8: SEQUENCE 5

Start

Grab Run State

Run = True

True

Go to Seq. 6

False

Grab Current Heading

Future Heading.Vi

Calculate Turning Radius

Radius Factor.Vi

Grab Current Heading

Grab Current Turning Voltage

Convert to Voltage

Calculate Turning Pulse Length

Current > Desired?

True

Pulse Left for Desired Time

False

Pulse Right for Desired Time

Store Values in Array

Grab First Map Coordinate

Grab Current Coordinate

Calculate Distance

Dist. < 3 m?

True

Go to Seq. 6

False

Go to Seq. 6
APPENDIX B-9: SEQUENCE 6A

1. Start
2. Grab Input Map
3. Grab Current Coordinate
4. Lookahead.Vi
5. Stop.Vi
6. Loop Timeout
7. Within Range
8. Grab Current Heading
9. Future Heading.Vi
10. Calculate Turning Radius
11. Radius Factor.Vi
12. Grab Current Heading
13. Grab Current Turning Voltage
14. Convert to Voltage
15. Calculate Turning Pulse Length
16. Current > Desired?
17. Pulse Left for Desired Time
18. Pulse Right for Desired Time
19. Store Values in Array
20. Continuation State Equals False
21. Go to Sequence 6b
APPENDIX B-10: SEQUENCE 6B

Start

Grab Continuation State

Continue? True →

Grab Current Coordinate

Grab Current Lookahead Coordinate

Calculate Distance

Distance < 3m? True →

Go to Sequence 6a

False →

Future Heading.Vi

Calculate Turning Radius

Radius Factor.Vi

Grab Current Heading

Grab Current Turning Voltage

Convert to Voltage

Calculate Turning Pulse Length

Current > Desired? True →

Pulse Left for Desired Time

False →

Pulse Right for Desired Time

Store Values in Array

Go to Sequence 7
APPENDIX B-12: GPS AND SENSOR DATA GATHER PROGRAM, SEQUENCE 0
APPENDIX B-13: GPS AND SENSOR DATA GATHER PROGRAM, SEQUENCE 0 (CONT.)

Grab Run State

Run? False

Go to Seq. 1

Run? True

Grab Previous Coordinate

Pull Current Coordinate from Queues

Current Heading.Vi

Store Values in Array
APPENDIX B-14: GPS AND SENSOR DATA GATHER PROGRAM, SEQUENCE 1

Start

Grab Data Arrays

Grab Log File Locations

Write Arrays to File

End
APPENDIX C: FLOW DIAGRAMS FOR PROGRAMS USED WITHIN LARGER PROGRAMS
APPENDIX C-1: LABJACK SCAN SEQUENCE STRUCTURE
(GATHERS SENSOR DATA FROM DAQ BOARD)
APPENDIX C-2: LABJACK SCAN SEQUENCE 0

Start

- Grab Turn Potentiometer Voltage
- Average Last Four Values
- Output Turn Potentiometer Voltage

- Grab Swash Plate Voltage
- Average Last Four Values
- Output Swash Plate Voltage

- Grab Cylinder Flow Voltage
- Average Last Four Values
- Output Cylinder Flow Voltage

- Grab Throttle Voltage
- Average Last Four Values
- Output Throttle Voltage

Iteration = 6?

- False
  - Go to Sequence 1

- True
  - Go to Sequence 1
APPENDIX C-3: LABJACK SCAN SEQUENCE 1

Start

- Grab RPM Voltage
- Grab Turn Pressure Voltage
- Grab Drive Pressure Voltage

- Average Last Four Values
- Average Last Four Values
- Average Last Four Values

- Output RPM Voltage
- Output Turn Pressure Voltage
- Output Drive Pressure Voltage

Iteration = 6?

- False
- True

End
APPENDIX C-4: LOOKAHEAD DETERMINER PROGRAM

Start

- Grab Input Array
- Grab Start Index
- Grab Current Coordinate
- Grab Start Time

Add 1 to Iteration #

Pull Iteration # from Input Array

Within Desired Range?

- True
  - Set Coordinate to Lookahead Value
  - Value = 1
  - Value = 0

- False
  - Value = 0

Calculate Length from Current Coordinate

Grab Current Time

Calculate Difference

Value > 5 s?

- True
  - End

- False
  - Value = 1
  - Value = 0

Value >= 1?

Sum

- True
  - End

- False
  - Value = 1
  - Value = 0
APPENDIX C-5: RADIUS FACTOR PROGRAM

Start

Grab Current Heading

Grab Previous Heading

Current > Previous?

Current - Previous

Abs. Value > PI?

Abs. Value > PI?

False

True

Current - Previous

Radius Factor = -1

End

Radius Factor = 1
APPENDIX C-6: THROTTLE CONTROL PROGRAM

Start

Grab Current RPM

Grab Desired RPM

Difference > 250 RPM?

Current > Desired RPM?

Decrease Voltage

Increase Voltage

End

True

False

False

True
APPENDIX C-7: CURRENT HEADING PROGRAM

Start

Grab Previous Longitude

Grab Current Longitude

Grab Previous Latitude

Grab Current Latitude

Calculate Difference

< 0? True

Value = 1

False

Value = 0

> or = 1? True

Determine Appropriate Cardinal Angle

False

Calculate Appropriate Angle

Sum

\[ \text{Value} = 0 \]

\[ \text{Value} = 1 \]

True

False

Sum

End
APPENDIX C-8: FUTURE HEADING PROGRAM

Start

- Grab Lookahead Longitude
- Grab Current Longitude
- Grab Lookahead Latitude
- Grab Current Latitude

Calculate Difference

- = 0?
  - True: Value = 1
  - False: Value = 0

< 0?

- True: Value = 1
- False: Value = 0

Sum

> or = 1?

- True: Determine Appropriate Cardinal Angle
- False: Calculate Appropriate Angle

End