TECHNICAL NOTE: EVALUATION OF A SIMPLE PURE PURSUIT PATH-FOLLOWING ALGORITHM FOR AN AUTONOMOUS, ARTICULATED-STEER VEHICLE

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TECHNICAL NOTE:

EVALUATION OF A SIMPLE PURE PURSUIT PATH-FOLLOWING ALGORITHM FOR AN AUTONOMOUS, ARTICULATED-STEER VEHICLE

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ABSTRACT. *A pure-pursuit navigational control algorithm in an autonomous articulated-steer vehicle was studied as a simple method for path-following. Paths were created using GPS coordinates and the articulated-steer vehicle programmed to follow those paths using a pure-pursuit (goal-seeking) path-following algorithm. A GUI was developed in LabVIEW to read RTK-GPS coordinates, hydraulic pressure and articulation angle, and control the articulated-steer vehicle. The vehicle was tested for its ability to follow five different paths with two speeds and three control pulse signals. Path following succeeded with lower vehicle speed and full pulse signal for the straight and sinusoidal paths. Averaged path-following errors ranged from 6 to 19 cm as the turn radius increased. For a 90 degree turn, the path-following error was almost 80 cm. Path-following improvements could be made with faster control signal updates and a variable look-ahead distance based on vehicle speed and required turning angle. It was concluded that the control architecture is a good basis for navigation of an articulated-steer autonomous vehicle.*

Keywords. *Autonomous guidance, Autonomous steering, Path-following, Pure-pursuit, Articulated-steering, RTK-GPS, Precision agriculture.*

Automated steering systems such as the Trimble AutoPilot, and John Deere's GreenStar Precision Solutions Autotrac allow farmers to follow crop rows extremely accurately; within ±2.5 cm (Deere & Co., 2013; Trimble, 2013). The driver is allowed to monitor the tractor operations while the system follows a pre-determined path using global positioning system (GPS) coordinates. The driver is also necessary to turn the vehicle around at the end of each row and to monitor the tractor systems. Navigation is based on tracking GPS coordinates using real-time kinematic (RTK) or virtual reference station (VRS) corrections through radio or cellular modem communications, respectively. Less accuracy is required for other applications, such as pasture spraying, and use cheaper and less precise differentially corrected GPS.

The level of guidance needed and the resulting strategies are dependent on the end result desired. Current auto-steering systems use a control algorithm and GPS receiver to steer the vehicle along pre-determined paths of GPS coordinates. Human monitoring is still required in commercial systems for emergencies (collision avoidance) and turning at the end of rows. Fully-planned tracking with the autonomy to turn at the end of the rows and with sensors to detect objects in its path are already available in prototype systems (Nagasaka et al. 2009; Bergerman et al., 2012). Unmanned aerial vehicles (UAV's) are gaining popularity in agricultural operations that include crop and livestock inspection and chemical spraying. Currently, the FAA prohibits the commercial use of UAV's in the United States. Ground vehicles could also perform operations that require closer proximity to the soil or plant, such as pest and disease detection, precision spraying, plowing, planting, and harvesting. Many tasks could be done 24 hours a day and data relayed to a server through a wireless Internet network. Internet access is now possible anywhere a cellular signal is available.

Obstacle avoidance, correct path-following, level of human-interaction, and implementation of unique applications are all important areas of study in agricultural field operations. Path-following allows for repetitive passes over the same course for land preparation, planting, chemical spraying, and harvesting operations. This control is used by auto-steering systems to reduce losses caused by uneven row spacing. For example, one study has shown that the use of automated guidance systems for deep tillage and planting of cotton could potentially reduce cotton yield losses by as much as 52% (Bergtold et al., 2009). Another

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study has shown that auto-steer tractors used to plant, dig and harvest peanuts reduced losses by over 18% (Vellidis et al., 2013). The ultimate goal is to have intelligent machines perform desired tasks with minimal or no human assistance.

Several studies have examined the ability to autonomously control an agricultural operation using sensors to guide the vehicle. A guidance system developed by Upchurch et al. (1983) 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 (2002) 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. More recent studies have examined advanced sensing and signal processing for improved guidance and control. Subramanian et al. (2006, 2009) developed a robot utilizing sensor fusion of machine vision and laser guidance with fuzzy logic controls to navigate through a citrus grove. Their system combined multiple sensors to detect environmental features and use resulting data to steer the vehicle. Similar studies of rice planters (Chen et al., 2003), a speed sprayer (Cho and Ki, 1999), and a weed control autonomous robot (Bakker et al., 2010) have employed optical, ultrasonic and GPS sensors for autonomous guidance. LiDAR (Light Detection and Ranging) is a popular choice for capturing 3-D landscape around a vehicle and determining the location of obstacles and desirable paths (Han et al., 2012; Garcia et al., 2012).

While there has been considerable research conducted to examine the guidance algorithms of the front-wheel and skid-steer vehicles, relatively little has focused on articulated-vehicle designs. In general, the path-following algorithm is independent of the steering mechanism. But, the electrical/mechanical/hydraulic control of the steering mechanism is dependent on the kinematic and dynamic characteristics of the physical system. Many articulated guidance studies examine the path-following from a truck and trailer perspective (Amidi, 1990, Martinez, 2002). In these studies, the truck (front) is pulling the rear (trailer) about the hitch point (articulation point). The control of such systems is different when compared to the articulated vehicle of this study. The two major differences are the controlled relationship between the front and rear, and the geometric relationship between the truck and trailer. Truck/trailer control depends on how the trailer moves respective to the truck. In the articulated tractor, the relationship between the front and rear are controlled by the hydraulic system of the tractor. Secondly, the trailer is much longer than the truck, resulting in a different geometry from an articulated tractor. The articulated tractor is geometrically symmetrical about the pivot point allowing for controlled guidance moving forward and backward (Faircloth, 2004).

This study examines the initial design of a GPS-based guidance system on an articulated-steer vehicle to follow a pre-determined path. The vehicle uses GPS data with RTK correction 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. (2002) 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 (1990) was shown to be a very accurate path following strategy with a 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. Accuracy of the path-following algorithm is dependent on the accuracy of the GPS, the rate of speed, the control pulse and the rate of direction change in the followed path. The vehicle speed is controlled by the tractor RPM's and the control pulse is the length of time the hydraulic control valve of the steering mechanism is engaged to apply a course correction.

The objectives of this study were to:

1. Implement a pure pursuit path-following algorithm on an articulated-steer vehicle, and
2. Test and evaluate the system's performance using five pre-determined paths, two engine speeds and three control pulse lengths.

Materials and Methods

System Setup

The vehicle used was an articulated steer tractor, Model No. 3420-Gc manufactured by West Texas Lee Co. (Idalou, Tex.; fig. 1). The tractor was powered by a 14.9 kW Kohler engine (Kohler Co., Kohler, Wis.) and motion delivered by a hydrostatic drive. The hydraulic pump used was an OILGEAR (The Oilgear Company, Milwaukee, Wis.) type PVW variable delivery hydrostatic pump. It was 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 were Danfoss (Sauer Danfoss Inc., Ames, Iowa) Geroler motors and delivered 315 cc/rev. The swash plate and throttle control were activated with an electrical linear actuator. Steering was controlled by an electrically actuated hydraulic solenoid valve. Depending on the desired direction, the valve supplied pressure to two hydraulic cylinders attached to both halves of the vehicle. When turning left, the left cylinder retracted and the right extended. Right turns were executed in the opposite manner. Electrical signals controlled all steering operations, which were on-off (bang-bang).

In conjunction with the actuators mentioned above, the vehicle had several sensors to provide vehicle status. A hall-effect rotary potentiometer (Honeywell International Inc., Morristown, N.J.) was mounted on the articulation point of the tractor to provide information regarding the angle of articulation. Pressure sensors (MSI, Hampton, Va.) were also implemented to measure hydraulic pressure in the drive and turning circuits. These sensors were included to

Figure 1. Articulated tractor used for path-following study (West Texas Lee Co., Idalou, Tex.).

monitor the vehicle system parameters remotely in the future. All sensors and actuators were connected to a LabJack (LabJack Corporation, Lakewood, CO) data acquisition board. The baud rate was 50 Hz. The LabJack was connected to the control computer through a USB connection (fig. 2). The control computer was a Dell Latitude D600 laptop, Model No. PP05L. It had a Pentium M processor (1.7 GHz, 1 GB RAM) and ran on the Microsoft XP Professional operating system.

Position data was obtained through a Trimble (Trimble Navigation Ltd., Sunnyvale, Calif.) AgGPS 214 RTK-GPS receiver, which relayed GPS data to the computer through an RS-232 serial connection. GPS coordinates were output to the control computer at a rate of 5 Hz. The receiver's antenna was mounted on top of the cab in the forward most position of the tractor and along the centerline. Horizontal static accuracy of the AgGPS 214 RTK-GPS system was 1 cm with base station in close proximity (<100m) (Trimble, 1999).

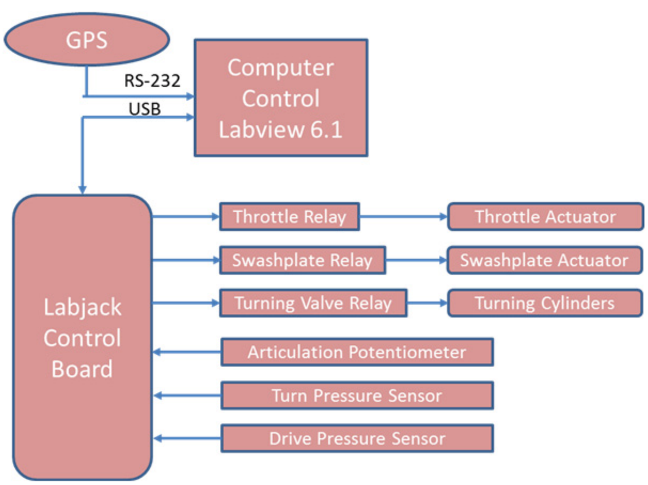

Figure 2. Basic components of system architecture for sensor input and control signal outputs using the Labjack, GPS, control computer, relays, and sensors.

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 not considered. The control program was written in LabVIEW (ver. 6.1, National Instruments Co., Austin, Tex.). Another LabVIEW program linked to the control program was developed to read data strings from the GPS receiver and convert the data to UTM coordinates (Faircloth, 2004). This additional program also determined 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 control program used heading, articulation angle and the look-ahead coordinate to make the decision on whether the left or right actuator needed to be initiated to obtain the desired turning radius.

The control architecture was based on the pure pursuit method used by Amidi (1990), which was a goal-seeking algorithm. Based on a predetermined look-ahead distance, the control algorithm computed the appropriate turning radius to achieve the desired look-ahead coordinate. Using the nomenclature of figure 3, the turning radius was derived from the relationships between x, y, r, L, and d. If $x+d = r$, and $d^2 + y^2 = r^2$, the relationship between r and the x, y coordinates can be solved to yield, $r = (x^2 + y^2) / (2x)$. Then since $L^2 = x^2 + y^2$, the relationship between r, L, and x becomes:

$$r = L^2 / (2x) \quad (1)$$

where

r = turning radius (m),

L = absolute distance between current and look-ahead coordinates (m),

x = relative distance between current and look-ahead coordinates (m).

The related curvature (γ) of the desired path is 1/r, so then by substitution into equation 1, the curvature is:

$$\gamma = (2/L^2)^*x \quad (2)$$

Consequently, the pure-pursuit algorithm was a proportional control algorithm where x was the displacement error and $2/L^2$ was the gain. To reduce the gain of the controller, the look-ahead distance was increased, and to increase the gain, the look-ahead distance was decreased.

As opposed to the vision system Amidi (1990) used to determine the look-ahead coordinates, the control algorithm developed for this project used an input map with pre-defined geo-spatial coordinates. By reading the current GPS coordinate and corresponding heading, the algorithm determined the future heading and the appropriate coordinate from the input map and calculated the turning radius required to achieve the look-ahead coordinate.

After computing the desired radius, the value was converted to the corresponding voltage value required at the articulation potentiometer. The relationship between the articulation voltage and radius was an inverse linear relationship shown as:

$$\gamma = \psi^*V + C \quad (3)$$

where

γ = inverse turning radius (m^{-1}),

ψ = slope in units of $(m\text{-}V)^{-1}$,

V = voltage at articulation potentiometer (V),

C = intercept in units of (m^{-1}).

Potentiometer was adjusted such that the voltage output was zero when the vehicle was moving straight ahead (articulation angle = 0). Consequently, C was always zero and ψ was determined by measuring the turning radius and potentiometer output for five articulation angles and taking the average. Solving for the desired potentiometer voltage:

$$V = (\gamma - C)/ \psi \quad (4)$$

After computing the desired voltage, the algorithm then compared the desired voltage to the current voltage. The difference in voltage was 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 s/V, was determined by recording the amount of time required to produce a 1 V change in the reading of the articulation potentiometer at full tractor RPM's. Corrections were made repeatedly until the vehicle's position was within the specified range (3 m) of the look-ahead coordinate. Once the vehicle's position was within the specified range, a new look-ahead coordinate was selected. The process repeated until the vehicle reached the end of the input path. A complete set of flow diagrams are found in Faircloth (2004).

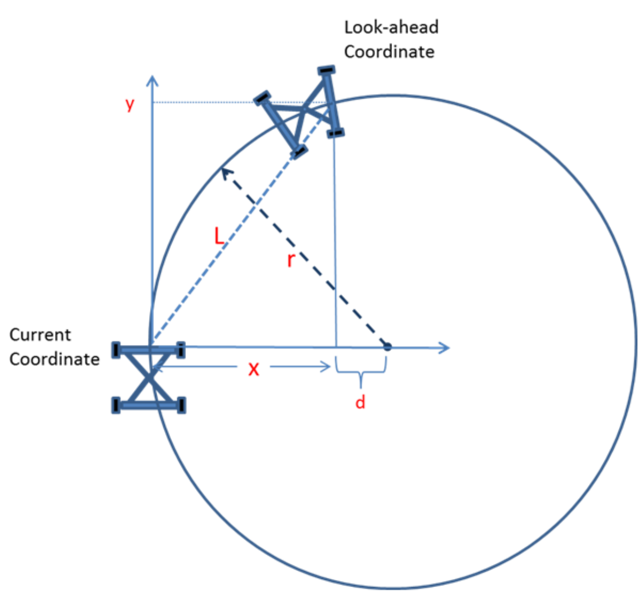

Figure 3. Control equation geometrical relationship between current and look ahead coordinate.

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 using the RTK-GPS system from the articulated vehicle, 47 m apart. The two GPS coordinates were converted to UTM coordinates in accordance with the location of the articulated vehicle in South Georgia, UTM Zone 17. Using the two UTM coordinates and Microsoft Excel, five different paths were developed. The first path was a straight line. The fifth path was a straight line with a 90° turn at the midpoint of the original straight line path. The remaining paths were sinusoidal, the amplitudes and wavelengths based on the minimum turning radius of the vehicle, which is approximately 2.7 m. In all cases, the amplitude was 3.5 m, which was slightly greater than the minimum turning radius. The wavelengths were multiples of 7.0 m, the diameter of a circle of minimum turning radius for the articulated vehicle at 2.4 km/h. The paths used are shown in figure 4.

In addition to the evaluation based on path following, speed and turning pulse lengths were varied. For each path, three different turning pulse signals were examined; full (1 s), half (0.5 s), and quarter (0.25 s). The turning pulse signal represents the length of time a turning signal was sent by the control program to the DCV solenoids. Because the vehicle has on-off turning controls (bang-bang control), the half- and quarter-pulse signals were used as a pseudo-proportional control by reducing the time a signal was sent to the DCV solenoids. Essentially, the half- and quarter-pulse signals 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 and 5.0 km/h. Each path was traversed five times with each speed and turning signal length combination. The distance between the RTK base station receiver and rover receiver was approximately 40 m.

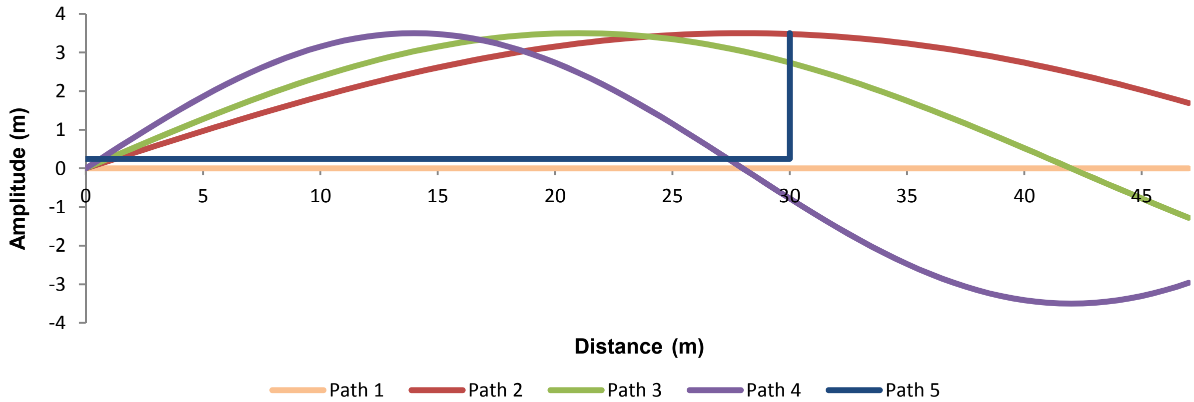

Figure 4. Paths generated in MS Excel for path-following tests. Path 1: Straight line; Path 2: Amplitude 3.5 m, Wavelength 56 m; Path 3: Amplitude 3.5 m, Wavelength 42 m; Path 4: Amplitude 3.5 m, Wavelength 28 m; Path 5: Straight with 90° turn. Both axes are in m.

PROGRAM EVALUATION

Error for each run was calculated by determining the minimum offset between the input map and the closest logged data point every 6 m. 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. 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.

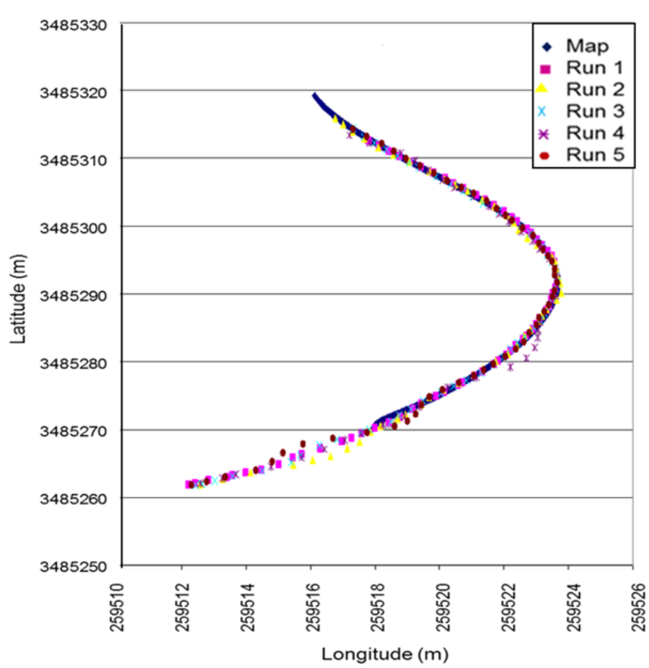

Figure 5. Representative data collected from path 2 at 2.4 km/h and full pulse. Tractor was moving from south to north. Figure not to scale.

RESULTS AND DISCUSSION

Figure 5 illustrates a representative graph of the five tractor runs following path 2 at 2.4 km/h. The mean and 95% confidence interval for all paths and turning pulse lengths at 2.4 km/h are shown in figure 6. The full-pulse and half-pulse signal results were not significantly different for all five paths. For the straight line and curved paths (paths 1-4), the full-pulse signal performed best with a maximum average path error of 19 cm in path 4. For the straight line path, average error was 6 cm. As the required turning radius in the path was increased (paths became more curved), error between the actual and desired paths increased for the full- and half-pulse signals. The quarter-pulse signal was not significantly different than the full- and half-pulse signal of the path 2 and 4 results. Mean errors were 0.90, 0.78, and 2.83 m, for paths 1, 3, and 5, respectively.

The results from Path 5 (fig. 6) show very clearly that the control system does not handle abrupt changes in direction well. The mean error is large, irrespective of the pulse signal. 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 was a clear relationship between vehicle characteristics and the maximum perpendicular deviation from the right-hand turn portion of Path 5 (fig. 7). Table 1 provides heading difference information for the current location and look-ahead point at the same instance. There are no conclusive trends. The angular difference depended on the location of the tractor when it detected the first look-ahead distance. The closer the vehicle was to the 90° turn when the next look-ahead coordinate was found, the larger the heading difference. This varied due to the imprecise location of the vehicle at the point of picking a new look-ahead coordinate. The half-pulse signal had the highest mean angular difference (φ), but was the most consistent over the five repetitions (lowest standard deviation). The most erratic φ value was from the quarter-pulse control signal results, which had the highest variability.

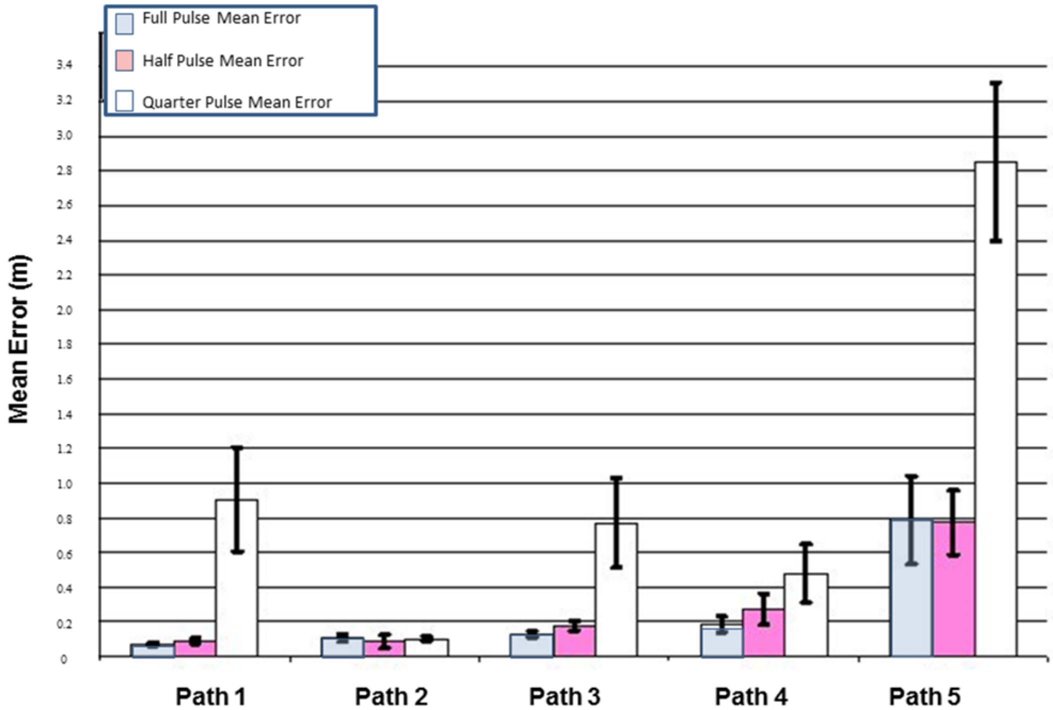

Figure 6. Mean error and 95% confidence interval for all pulse rate and path combinations at 2.4 km/h.

When the speed was increased from 2.4 to 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.

By reviewing paths of travel by the articulated tractor in this study, the slow update rate of the control program did 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. Average update time for the control algorithm was 3 s. Consequently, the next look-ahead coordinate was picked up every 2.0 and 4.1 m of travel at 2.4 and 5 km/h, respectively. With 6 m between GPS coordinates, the necessary turn radius to return to the path increased as the speed increased. Figure 8 illustrates a severe correction situation caused by the distance traveled between control commands at the higher speed. As can be seen in the figure, by correction 3 the articulated vehicle is severely off course and must make abrupt changes in heading to follow the GPS look-ahead coordinates.

Based on the results obtained from the series of tests performed on the control architecture, several observations were made about the abilities and deficiencies of the control system. First, figure 6 shows that the control

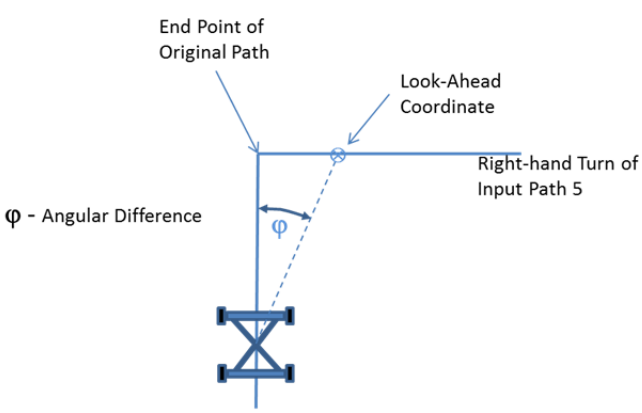

Figure 7. Relationships for tractor with respect to Path 5. Actual angular difference (φ) values are in table 1.

Table 1. Angular difference measured between the current heading and the desired heading at the first look-ahead point on the right-hand turn portion of Path 5 with each pulse rate.

Pulse	Run	Angular Difference, φ (°)
Quarter	1	47.343
	2	24.044
	3	16.143
	4	69.145
	5	-1.979
	Mean	30.939
	Std. Dev.	27.74368
Half	1	52.602
	2	58.121
	3	29.099
	4	47.582
	5	22.663
	Mean	42.013
	Std. Dev.	15.36068
Full	1	55.883
	2	56.291
	3	34.379
	4	42.167
	5	-0.343
	Mean	37.675
	Std. Dev.	23.20828

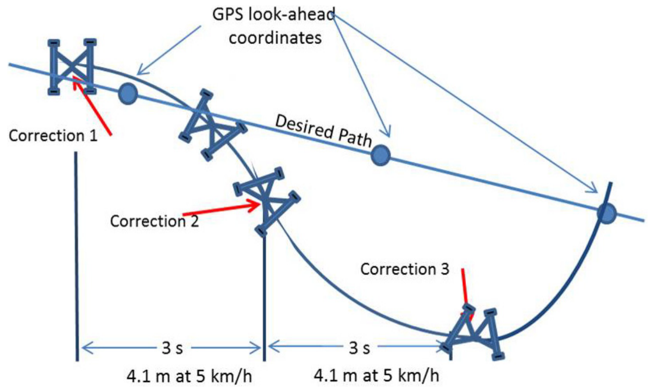

Figure 8. Demonstration of correction problem that occurs by calculating heading from GPS look-ahead coordinates when speed of vehicle is too fast for the control algorithm.

architecture produced accurate path following using the combination of a goal-seeking approach and GPS data for position information when the vehicle was running at a proper speed. The results also showed that the use of the half-pulse signals worked well for the straight paths as was previously believed. The quarter-pulse signal, which was thought to have benefited situations of minimum change in direction, did not work well. The change in turning radius made during a quarter-pulse signal was not fast enough to control the articulated vehicle, especially as the path changes became more abrupt. In general, the only advantage to using the half-pulse signal was that it produced less overshoot of the desired path than the full-pulse signal.

For increased ground speed, the control architecture needed improvement. Slow data acquisition and the operating speed of the hardware limited the update rate to 3 s using a laptop computer to manage input and output signals. A stand-alone embedded control system would reduce the overhead used by an operating system. The way in which the goal-seeking approach was implemented was also believed to be a contributing factor to tractor misalignments. After determining the look-ahead coordinate, the vehicle made adjustments to reach that point until it was within 3 m. The data showed that this method worked well at low speed. Amidi's approach, however, determined a new look-ahead 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. In addition development of a variable look-ahead distance (variable gain) based upon the speed of the vehicle and required turning radius would improve the high speed path following ability. If that were implemented, the path followed by the autonomous vehicle would also require coordinates at intervals less than 6 m.

Some additional issues were the methods used to calculate heading and look-ahead coordinates. Though the GPS receiver output data at a rate of 5 Hz, the LabVIEW "GPS Read program" output new coordinate and heading values at a slower rate of 2.5 Hz. The heading calculations for the tractor were based on current and old position values. The result, especially in cases of tight turning, was a large angular difference in actual and calculated heading values. This problem could be alleviated by replacing the calculated heading values with the output of an electronic compass. The compass would provide more accurate data by giving exact heading values at the time new heading is calculated, independent of previous positions. In addition, error could be reduced if multiple look-ahead coordinates were used to help improve the orientation of the vehicle before it gets too far from its path.

CONCLUSIONS

A pure-pursuit path-following algorithm was implemented and tested on an articulated vehicle. Five paths were created in UTM coordinates and used to test the path-following ability of the developed algorithm. The path-following algorithm on the articulated vehicle was tested at two speeds and three turning control pulse signals for the five paths.

For the lower speed, 2.4 km/h, the vehicle followed the paths 1-4 with average error ranging from 6 to 19 cm for the full-pulse signal. This level of accuracy would most likely be sufficient for pasture and turf grass spraying or remote farm monitoring with a camera and cellular modem. For path 5, the 90° turn, average error was almost 80 cm. The half-pulse control signal did not have a significant effect in reducing error and the quarter-pulse signal had the largest errors in path-following. It was concluded that the lower pulse signal did not change the turning radius sufficiently to follow the paths at the 3 s update rate. An embedded processor was recommended to improve update time and improve path following.

Future modifications to the articulated vehicle will include a compass to determine heading as opposed to determining heading based upon calculations made from subsequent GPS coordinates. This was particularly relevant when the past heading was used and the tractor had made a sharp turn. In addition, to improve the overall path-following ability, a variable look-ahead distance and paths that have an interval between GPS coordinates of less than 6 m will be tested. In addition, increasing the number of look-ahead coordinates used to make turning decisions will also be examined as a method to reduce path error. These improvements become more significant factors as the vehicle changes speed and/or the turns in the path become more severe.

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