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IFAC-PapersOnLine 49-16 (2016) 039–044

Steering Control Strategies for a Four-Wheel-Independent-Steering Bin Managing Robot

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Abstract: Automatic steering systems are a standard function for robotic agricultural equipment. Ackerman steering is the most common type of steering mechanism on such equipment, making them perform as car-like vehicles. Because of their kinematic constraints, it is quite difficult to maneuver car-like vehicles effectively in orchards due to confined working space, constrained by physical boundaries such as tree rows and other obstacles. To remove such technical difficulties, more sophisticated steering mechanisms and steering control strategies are required for robotic agricultural equipment. In order to conveniently manage fruit bins in confined tree aisles constrained by high density tree rows, a robotic bin management system, called bin-dog system, implementable in typical Washington State tree fruit orchards has been developed. This bin-dog system adopted a four-wheel-independent-steering (4WIS) mechanism as the solution to achieve the necessary drivability and maneuverability. To provide adequate controllability to this 4WIS, a four-mode steering strategy, including Ackermann steering, active front and rear steering (AFRS), crab steering, and spinning, were designed for this bin-dog to manage fruit bins effectively in the confined orchard space . This control system makes it possible for the bin-dog system to switch between four steering modes using the most appropriate steering mode to complete all maneuvering tasks in a most effective way. To design such a control system, it is important to understand the influence of major factors, such as longitudinal speed and control gain on performance under different steering modes when tracking various paths. In this paper, a pure pursuit method was implemented using a GPS-based navigation to evaluate auto-steering performance with both Ackermann steering and AFRS modes. Field tests were conducted to assess the navigation performance using different steering strategies when tracking different paths. The results indicated that by properly selecting a steering strategy for the situation, it is possible to achieve a satisfactory path tracking performance for tracking curvy paths or completing tasks such as merging and cornering.

Keywords: *Steering control systems, global positioning systems, four-wheel-independent-steering system*.

1. INTRODUCTION

The application of auto-steer technology on agricultural equipment in North America can be traced back to the early 1920s. A patent depicted automatic steering systems that could guide a tractor to follow furrows across a farm field (Willrodt, 1924). With the development of computing units and sensor technologies, auto-steer technology has gained a much wider application in agriculture. Numerous reported studies verified that auto-steering could help achieve good driving accuracy while maintaining a high driving speed and at the same time releasing the operator from monotonous driving to reduce fatigue and improve driving performance (O'Connor et al., 1996; Zhang and Qiu, 2004; Roberson and Jordan, 2014).

Most auto-steer technologies for conventional agricultural equipment were based on Ackerman steering, a car-like vehicle steering mechanism which is typically a nonholonomic system. Admissible directions of motion are restricted for nonholonomic systems due to their kinematic constraints. Thus when environmental constraints such as bounded driving paths and obstacles in confined job sites are taken into account, path planning and equipment maneuvering for automatic nonholonomic systems become difficult.

An auto-steered vehicle for tree fruit orchards use needs to effectively and safely maneuver in aisles formed by tree rows, as well as quickly and precisely steer in and out those aisles (Freitas et al., 2012; Subramanian and Burks, 2007). One unique feature of working in orchard environments is its confined space which makes correcting poses on an aisle or steering the vehicle into an aisle without multiple trials and corrections very challenging if the equipment uses only the Ackerman steering mechanism. Four-wheel-independent-steering (4WIS) is one solution capable of improving both the drivability and the maneuverability of orchard vehicles operating in confined space. When designing robotic mobile orchard equipment, the development of capable auto-steer systems for 4WIS vehicles is essential. Research on developing the needed technologies has been reported in recent years. For example, Bak and Jakobsen (2004)

10.1016/j.ifacol.2016.10.008

reported the development of a robotic platform with 4WIS system for weed detection. Its navigation controller utilized two control points (front end and rear end) independently to minimize the distance needed to reference a trajectory. Oksanen and Backman (2007) used kinematic and dynamical models to steer both front and rear axles of their 4WIS platform. Nagasaka et al. (2004) introduced an autonomous field watching-dog robot with 4WIS, with different steering modes to implement appropriate steering strategies for driving between rows and turning around at headland of a field.

To create a solution for efficiently and safely managing fruit bins, researchers from Washington State University (WSU) Center for Precision and Automated Agricultural Systems (CPAAS) have developed a robotic bin-dog system with a 4WIS system for transporting bins in typical Pacific Northwest (PNW) tree fruit orchards (Ye et al., 2016). A 4WIS system is able to turn each wheel independently to increase the maneuverability to omnidirectional by properly coordinating the turning of all wheels. Such a capacity allows a robot to turn at any instantaneous center of rotation (ICR) and provides for the ability to drive the bin-dog in confined orchard environments. A capable bin-dog steering control system plays a role in achieving required path tracking and bin maneuvering performance, which is influenced by longitudinal driving speed, steering modes, control gain, and path patterns. The goal of this study was to investigate the influence of the identified factors, including robot longitudinal driving speed, steering modes, control gain, and path patterns, on the bin-dog steering performances on path tracking and bin maneuvering in orchard environments. The outcomes from this study will provide guidelines for developing adequate steering strategies for the bin dog robot to perform required bin management operations.

2. MATERIALS & METHODS

2.1 Bin-Dog research Prototype and 4WIS System

A bin-dog research prototype (Figure 1) for bin management in orchard environment was designed and fabricated as a research platform to investigate the influencing factors for different auto-steering strategies.

Fig. 1. A 4WIS robotic bin-dog research prototype

The 4WIS system on this bin-dog prototype was made of an electrohydraulic system driven by a 9.7 kW gas engine (LF188F-BDQ, LIFAN Power, China). Driven by a load sensitive pump (Series P1, Parker Hannifin, OH, USA), the drive chain used four low-speed high-torque hydraulic motors (TL series, Parker Hannifin, OH, USA) to drive the wheels and four hydraulic rotary actuators (L10-9.5, HELAC, WA, USA) to steer those wheels. Eight bidirectional proportional electrohydraulic valves (Series VPL, Parker Hannifin, OH, USA) were used to control those actuators individually. The rotational speed of each wheel was measured using four optical incremental encoders (TR2 TRU-TRAC, Encoder Products, ID, USA) and their steering angles were measured using four absolute encoders (TRD-NA720NWD, Koyo Electronics Industries, Tokyo, Japan). All steering wheels have a maximum steering angle of 90° which makes it possible for the 4WIS system to place its ICR at any location.

2.2 Steering Modes of 4WIS

In order to simplify the control strategy and at the same time maximize maneuverability of the bin-dog system in confined working space, four steering modes, namely Ackermann steering, active front and rear steering (AFRS), crab steering, and spinning steering (as illustrated Figure 2), were used in this study. When Ackermann and AFRS steering are implemented, the bin-dog will change its orientation and driving direction and keep moving in longitudinal directions. In spinning, it changes the bin-dog orientation without changing its position and crab steering just does the opposite. Thus spinning and crab steering could be effective when only orientation or position correction is required.

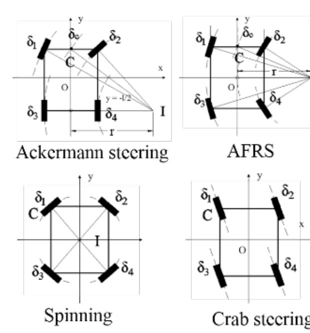

Fig. 2. Four steering modes of 4WIS

Our previous work (Ye et al., 2016) has described the detailed information of a 4WIS control system for this bin-dog. Laboratory tests on paved ground showed that under the maximum longitudinal speed of 1.2 $m \cdot s^{-1}$, this bin-dog 4WIS system could achieve a maximum steering speed of $30^{o} \cdot s^{-1}$ with a maximum error of ±3.0°. To avoid excessive mechanical stress caused by large steering angle, the minimum turning radiuses of Ackermann steering and AFRS were set at 1.7 m and 2.3 m respectively.

2.3 GPS-Based Navigation System

As one of the simple geometric path trackers, pure pursuit method showed a robust performance (Snider, 2009; Rains et al., 2014). By pure pursuit method, a bicycle model is used to simplify vehicle models. For a robot working in orchard environment, its longitudinal speed generally is low (less than 10 $m \cdot s^{-1}$), thus both Ackermann steering and AFRS could be simplified using bicycle models without losing much accuracy. Mostly commonly used in Ackermann steering analysis as shown in Figure 3(1), the pure pursuit method could be easily modified for AFRS applications (Figure 3(2)).

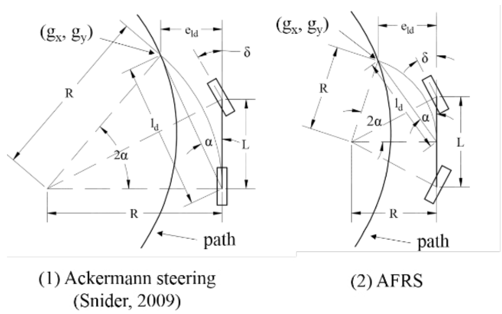

Fig. 3. Pure pursuit geometries for Ackermann and AFRS steering

In Figure 3, R is the turning radius; l_d is the look-ahead distance; α is the angle between look-ahead vector and heading vector of the vehicle; δ is the vehicle steering angle and e_{ld} is the distance from goal point to heading vector. The pure pursuit method connects a control point on vehicle and a goal point on path using a circular arc. The goal point (g_x, g_y) is found by calculating a look-ahead distance from the control point to the path. For Ackermann steering, the control point is typically set at the mid-point of its rear axle, while for AFRS, the control point is often set at its geometric center. The curvature of the circular arc κ for Ackermann steering could be calculated using following equation (Snider, 2009):

$$\kappa_{ACKER} = \frac{2}{l_d^2} e_{l_d} \tag{1}$$

Based on the geometry of bicycle model for Ackermann steering, by defining vehicle steering angle as the steer angle in the bicycle model, it could then calculated:

$$\delta_{ACKER} = \tan^{-1}(\kappa_{ACKER} L) = \tan^{-1}\left(\frac{2Le_{l_d}}{l_d^2}\right) \tag{2}$$

The curvature of the circular arc and steering angle for AFRS can be calculated using a similar approach:

$$\kappa_{4WCS} = \frac{2}{l_d^2} e_{l_d} \tag{3}$$

$$\delta_{4WCS} = \tan^{-1}\left(\frac{\kappa_{4WCS} L}{2}\right) \tag{4}$$

Once desired driving speed and vehicle steering angle are determined, the speed and steering angle of each wheel can be calculated accordingly.

A RTK-GPS receiver (AgGPS432, Trimble, Sunnyvale, CA, USA) with claimed 3 cm positioning accuracy was used for tracking the positioning of the bin-dog in all tests. The heading angle of bin-dog was measured using an IMU (AHARS-30, Xsens, Netherlands).

2.4 Experiment Design

2.4.1 Path Tracking on Curvy Paths

Capable of following curvy paths accurately is one of the basic requirements for an auto-steer system. To investigate the influence of different factors on path tracking performance on curvy paths, Lemniscate curves, having a shape of a figure of eight as shown in Figure 4, were used as the test courses. Because it consists of changing radius, Lemniscate curve is often used to assess maneuverability of a steering system.

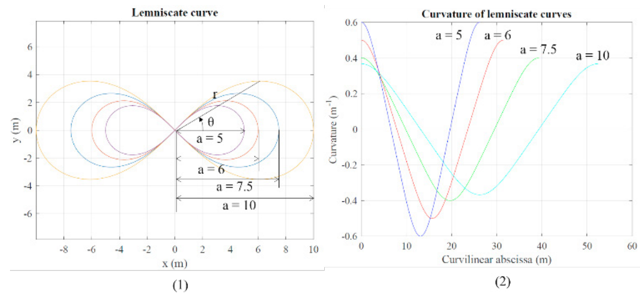

Fig. 4. Lemniscate curves for testing maneuverability of a steering system

Such Lemniscate curve can be described using polar equation below:

$$r = a\sqrt{\cos(2\theta)} \tag{5}$$

In which both r and θ are its polar coordinates. The value of a equals the distance between origin to the right most point of the curve. Thus the size of Lemniscate curve which closely relates with its curvatures can be controlled by changing the value of a. The minimum radius of curvature of a Lemniscate curve can be calculated using equation below:

$$R_c = \frac{a}{3} \tag{6}$$

Figure 4 also illustrates the curvatures of test courses with different values of a. As the value of a increases, the size of Lemniscate curve as well as the minimum radius of curvature also increase and the rate of change of curvature becomes milder.

In this study, three sets of tests were conducted on uneven soft soil ground in natural environment using both Ackermann and AFRS steering modes. In the first set tests, the bin-dog was guided using an auto-steer system to track four Lemniscate curves of different sizes (a = 5, 6, 7.5, and 10 m) with a fixed longitudinal driving speed of 0.6 m·s^{-1} and fixed look-ahead distance of 1.0 m for Ackermann steering and 0.75 m for AFRS steering. In the second set tests, five different longitudinal speeds (0.4, 0.5, 0.6, 0.8, and 1.0 m·s^{-1}) were used with a fixed look-ahead distance of 1.0 m for Ackermann steering and 0.75 m for AFRS steering to track a Lemnicate curve with a value of 10 m. In the third set of tests, five different look-ahead distances (0.8, 0.95, 1.0, 1.1, and 1.2 m) for Ackermann steering, (0.65, 0.7, 0.75, 0.85, and 0.95 m) for AFRS steering were used with a fixed longitudinal speed of 0.6 m·s^{-1} to track the same Lemniscate curve as used in first set of tests. The range of look-ahead distances for a steering mode was determined so that it could cover a look-ahead distance which gave a satisfactory path tracking performance. Therefore, the test could reveal the influence of look-ahead distances around a satisfactory setting over path tracking performance. All the combinations were conducted with three replications.

2.4.2 Merging, Straight Line Tracking and Cornering

As mentioned above, steering a bin-dog into an aisle from headland is frequently needed during bin management. This process involves actions including merging which allows platform to reach desired path without changing its original heading angle and cornering which allows platform to turn 90° to enter aisles from the headland. In order to design a steering strategy for tasks of merging and cornering, it is important to investigate influence of factors such as longitudinal driving speed, control gain, and steering modes on work efficiency and spatial requirements. Figure 5 shows a test course used for testing this function.

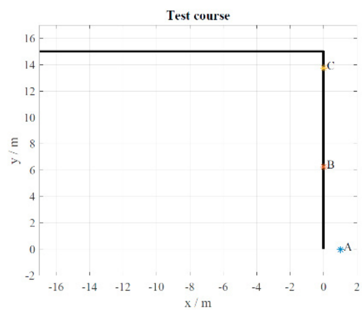

Fig. 5. Test course for merging, straight line tracking and cornering

The test path consists of two segments connected by a 90º turning point as illustrated in Figure 5. In the series of tests, the bin-dog started from point A, which was 1 m to the right of the beginning of headland path (represented by the vertical line in the figure), merged to the desired headland path, took a 90° turn to the left entering the aisle, then followed the path in the aisle (presented by the horizontal line) until reaching the target location. As the testing path has a right turn which is mathematically discontinuous, it is impossible for nonholonomic systems such as Ackermann and AFRS systems to follow this path precisely. This study planned and conducted all three sets of tests on uneven soft soil ground to investigate the performance of different steering modes on such a path. In the first set tests, four different longitudinal speeds (0.4, 0.5, 0.6, and 0.8 $m \cdot s^{-1}$) were used with a fixed look-ahead distance of 1.1 m for Ackermann steering and 1.1 m for AFRS steering to track the desired path. In the second set, five look-ahead distances each for Ackermann steering (0.95, 1.0, 1.1, 1.2 and 1.5 m) and for AFRS (0.8, 0.9, 1.0, 1.1 and 1.2 m) were used with a fixed longitudinal speed of 0.6 $m \cdot s^{-1}$ to track the path. In the third tests, three steering modes were used in combination to complete the entire test course. Crab steering was firstly used to merge with the headland path from the start point A. The navigation system kept calculating steering angle using the location information of bin-dog control point. Once the control point was close enough to point B on the desired path, the steering mode automatically switched to Ackermann steering. The Bin-dog then kept tracking the headland path till its control point reached point C which was 0.47 m (half of the wheel base) below the corner. The bin-dog would stop at point C, turn the steering mode into spinning and, rotate 90°on its geometry center to set its orientation in parallel to aisle path. The bin-dog then switched steering modes back to Ackermann steering to track in-aisle path till it reached the target point. Five longitudinal speeds (0.4, 0.5, 0.6, 0.8, and 1.0 $m \cdot s^{-1}$) were used with the look-ahead distance of Ackermann steering being fixed at 1.2 m.

3. RESULTS AND DISCUSSION

3.1 Path Tracking on Curvy Paths

Figure 6 and Table 1 provide the results obtained from Lemniscate curves tracking performance from field tests. Two important parameters that influence path tracking performance are minimum radius of the curvature and rate of curvature. The minimum turning radius of Ackermann steering system for this bin-dog research platform was 2.3 m while the minimum radius of curvature of Lemniscate curve with *a*-value of 5 m was 1.7 m. Thus it is impossible for Ackermann steering to perfectly track this curve. AFRS has a minimum turning radius of 1.7 m which gave it better performance when the radius of curvature of the path is small. The path tracking trajectory showed in Figure 6(1) revealed that the lateral error of the bin-dog in tacking the smaller curve was noticeably larger. As an AFRS system has much smaller minimum turning radius, and it could achieve a much better path tracking performance on the small curve than Ackermann steering (as shown in Figure 6(2)).

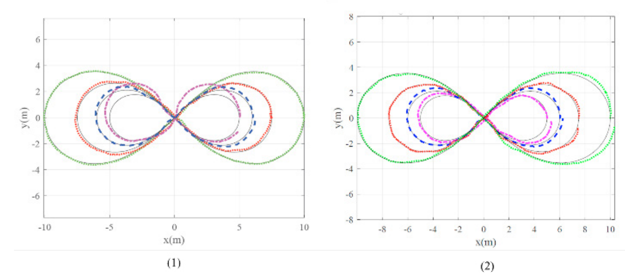

Fig. 6. Path tracking of Lemniscate curves of different radius

Table 1 Path tracking performances on Lemniscate curve of different sizes with Ackermann and AFRS steering

a-value (m)	Lateral error					
	Ackermann Steering			4WCS		
	Mean (m)	Std-dev (m)	Max (m)	Mean (m)	Std-dev (m)	Max (m)
5.0	0.35	0.33	1.39	0.13	0.13	0.58
6.0	0.10	0.09	0.41	0.15	0.06	0.38
7.5	0.26	0.16	0.57	0.07	0.06	0.23
10.0	0.05	0.04	0.60	0.10	0.08	0.44

Table 2 lists the results for tests in different longitudinal speeds in detail. Both Ackermann steering and AFRS successfully completed the test course under all speed levels (expect for AFRS under 1.0 $m \cdot s^{-1}$ due to frequently engine stalls). As expected, a lower longitudinal speed could always results in a higher tracking accuracy (with a lower mean lateral offset, standard deviation, and maximum offset). That is because a lower longitudinal speed allows the bin-dog steering actuating system to have sufficient time to respond to input steering command to correct any observed path tracking error. It could also help to reduce lateral wheel slip and allowed pure rolling on all four wheels. Thus a bin-dog at low longitudinal speed could stay on the reference curve and maintain a satisfactory and stable path tracking performance. This finding revealed a need that the bin-dog steering system have good control performance to satisfactorily support high speed operations as it would require more frequent corrections to make the vehicle track precisely on its desired path under all disturbances. The steering system tends to oscillate in large amplitude when the system response frequency is low resulting in large maximum lateral offset and standard deviation.

Table 2. Path tracking performances of Ackermann and AFRS steering at different longitudinal speeds

Speed ($m \cdot s^{-1}$)	Lateral error					
	Ackermann Steering			AFRS Steering		
	Mean (m)	Std-dev (m)	Max (m)	Mean (m)	Std-dev (m)	Max (m)
0.40	0.06	0.03	0.19	0.03	0.02	0.16
0.50	0.13	0.06	0.39	0.06	0.04	0.37
0.60	0.05	0.04	0.31	0.10	0.08	0.44
0.80	0.19	0.10	0.60	0.10	0.10	0.66
1.00	0.21	0.23	1.12	/	/	/

Table 3 summarized the obtained path tracking performance of the bin-dog tested when different look-ahead distances were applied. The look-ahead distance is the only control gain for tuning auto-steer system using the pure pursuit method.

Table 3. Path tracking performances of Ackermann steering and AFRS steering with different look-ahead distances

l_d (m)	Lateral error			l_d (m)	Lateral error		
	Ackermann Steering				AFRS Steering		
	Mean (m)	Std-dev (m)	Max (m)		Mean (m)	Std-dev (m)	Max (m)
0.80	0.06	0.04	0.23	0.65	0.20	0.14	0.82
0.95	0.05	0.04	0.31	0.70	0.06	0.06	0.31
1.00	0.07	0.06	0.42	0.75	0.10	0.08	0.44
1.10	0.23	0.16	0.68	0.85	0.12	0.08	0.36
1.20	0.30	0.13	0.80	0.95	0.16	0.16	0.63

Typically, the look-ahead distance is tuned for different longitudinal speeds. Based on equations (2) and (4), a longer look-ahead distance will generate a smaller steering angle to correct the same level of lateral errors and cause an under-correction. Because of that a long look-ahead distance usually responds slowly in correcting a lateral error. A long look-ahead distance may also cause overlooking some signature points just in front of the moving vehicle and result in a poor tracking performance. Therefore when tracking curvy paths with changing radius, it should control the look-ahead distance carefully to avoid a too long distance to ignore the "just-in-front" signatures and result in large lateral offsets. A short look-ahead distance is usually more sensitive to lateral errors which makes it often generate relatively larger steering correction signal than needed and cause over-correction. The steering tends to oscillate and the system becomes unstable leading to poor tracking performance when look-ahead distance is set too short as in the case of AFRS steering with l_d being set at 0.65 m. In general, long look-ahead distance is suitable for high speed operation and short look-ahead distance is suitable for low speed.

3.2 Path Tracking on Merging and Cornering

Figure 7 shows the trajectories of the bin-dog turning 90° into an aisle using AFRS only mode and multi-modes. In the Figure, D1 and L1 represent for the width and length for completing merging while D2 and L2 represent for the width and length for cornering. For both Ackermann and AFRS steering, some noticeable overshoots can be observed during merging and cornering on those places. When the auto-steer system tries to complete merging and cornering, it needs to correct both offset error and heading angle error. However, it is impossible for Ackermann steering or AFRS steering to eliminate both errors at the same time, and some overshoots will unavoidably occur.

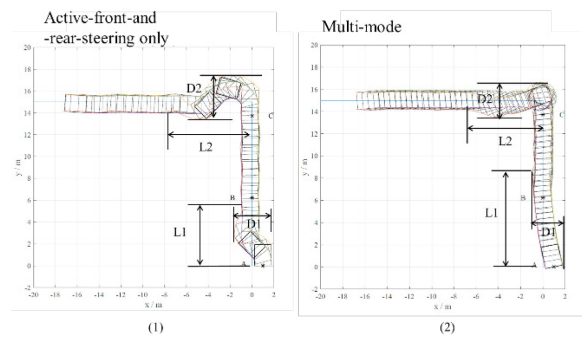

Fig. 7. Path tracking result for merging and cornering using active-front-and-rear-steering only and multi-mode.

Tables 4 and 5 provide a summary of the required space for correcting merging and cornering overshoots (D1 and D2).

Table 4. Merging and cornering performance of different steering modes at different longitudinal speeds

Mode	v ($m \cdot s^{-1}$)	T1 (s)	T2 (s)	D1 (m)	D2 (m)	L1 (m)	L2 (m)
Multi-mode	0.40	29.70	21.83	2.71	2.70	7.05	0.23
	0.50	22.63	15.83	2.73	2.84	7.80	0.92
	0.60	19.63	15.10	2.76	3.03	10.50	0.50
	0.80	14.17	13.17	2.79	2.78	9.37	3.04
	1.00	11.07	14.87	2.69	2.99	11.17	4.24
AKMN	0.40	16.70	35.27	3.13	4.33	3.84	7.13
	0.50	12.20	38.10	3.13	5.13	3.67	9.69
	0.60	8.47	33.53	3.16	5.29	3.38	10.01
	0.80	7.40	/	3.28	/	4.73	/
AFRS	0.40	17.53	34.70	3.16	4.13	3.03	2.24
	0.50	10.90	24.73	3.22	4.15	2.91	5.23
	0.60	8.37	30.87	3.20	4.62	3.15	6.50

In table, v: Longitudinal speed; T1, T2: Time used for merging and cornering; D1, L1: space and length required for merging; D2, L2: space and length required for cornering; AKMN: Ackermann steering.

This space is increased as the longitudinal speed increases for both Ackermann and AFRS steering. As discussed earlier, a long look-ahead distance tends to ignore some "just-in-front" path signature points such as the discontinuity point for merging and cornering. So while it could help reduce overshoots and smooth the trajectories, it will have some difficulty making precise 90° turns.

The length required for merging and cornering (L1 and L2) will decrease as the longitudinal speed goes down. However there is no clear relationship with look-ahead distance.

Generally, a short look-ahead distance tends to make oscillation in path tracking and a long look-ahead distance is slow to steer the vehicle back on track. Thus both could result in long L1 and L2.

The time required to complete merging and cornering (T1 and T2) is often related to robot longitudinal speed. Normally, a higher longitudinal speed could substantially reduce the time needed for merging the robot back to track, but may also require a longer distance to complete cornering and turning in a tree aisle. The data acquired from field tests revealed that the differences in time required to complete a turn were rather small within all tested longitudinal speeds.

Table 5. Merging and cornering performance of different steering modes with different look-ahead distances

Mode	l_d (m)	T1 (s)	T2 (s)	D1 (m)	D2 (m)	L1 (m)	L2 (m)
AKMN	0.95	12.97	31.60	3.33	5.20	3.39	13.24
	1.00	10.10	40.30	3.27	5.78	3.38	10.01
	1.10	8.47	33.53	3.16	5.29	3.19	7.27
	1.20	9.50	25.05	3.10	4.29	3.72	6.09
	1.50	10.97	23.83	2.96	4.04	4.71	6.87
AFRS	0.80	15.90	37.20	3.90	5.14	4.45	7.90
	0.90	17.85	33.70	3.72	5.14	2.89	6.60
	1.00	10.25	25.90	3.24	4.79	3.15	6.50
	1.10	8.37	30.87	3.20	4.62	3.19	5.55
	1.20	11.40	22.60	2.27	3.89	3.39	13.24

As afore discussed, compared to Ackermann and AFRS steering, crab steering is more effective in translating which allows correcting the position error without changing vehicle heading orientation. Thus it is more effective in merging. As shown in Table 4 and 5, it required minimum space to merge back on track. The long length for merging in multi-mode steering was because the correction was targeted at setting location of point B. If the B location was moved closer to point A, it could substantially reduce the required merging length. In cornering, spinning mode is the most effective method to correct vehicle heading orientation without changing its location. Thus it took least space to complete cornering.

Crab steering can be smoothly switch to or back from either Ackermann or AFRS steering without stopping the vehicle, but stops are required for switching to or back from spinning. If continuous driving is required, even though spinning requires the least space for turning, Ackermann or AFRS steering is still preferred.

4. CONCLUSIONS

In this study, with the influence of different longitudinal speeds, look-ahead distances, and path curvatures of different steering modes were investigated in terms of their auto-steer performances when tracking a few specially designed test courses. The results indicated that both Ackermann and AFRS steering could achieve satisfactory path tracking performance within the permissible limits of corresponding physical configurations. Obtained results also verified that crab steering and spinning could effectively reduce the spatial requirement for merging and cornering compared to Ackermann or AFRS steering. Based on this work, the future work will focus on developing a dynamic control system to dynamically choose optimal steering strategy for the situation in terms of the longitudinal speed, look-ahead distance, and path curvature.

ACKNOWLEDGEMENTS

This research was partially supported in part by United States Department of Agriculture (USDA)'s Hatch and Multistate Project Funds (Accession No 1005756 and 1001246), USDA National Institutes for Food and Agriculture competitive grant (Accession No 1003828), and Washington State University (WSU) Agricultural Research Center (ARC). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture and Washington State University.

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