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STEERING STRATEGY SELECTION OF A ROBOTIC PLATFORM FOR BIN MANAGEMENT IN ORCHARD ENVIRONMENT

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Abstract. *For a robotic bin-managing system working in an orchard environment, especially in modern narrow row spaced orchards in the Pacific Northwest (PNW) region of the U.S., path planning is an essential function to achieve highly efficient bin management. Unlike path planning for a car-like vehicle in an open field, path planning for a four-wheel-independent-steered (4WIS) robotic bin-managing platform in orchard environment is much more challenging due to the very confined working space between tree rows. Subject to the unique constraints of worksite space and operation limits, different steering modes are often required to accomplish the desired bin handling maneuvering actions effectively, or sometimes even all. In this study, we proposed a path planning algorithm to guide the robotic system in accomplishing several designated bin management tasks effectively, such as correcting pose error between tree rows; entering a tree lane from the headland; and loading a bin between tree rows. The path planning algorithm selects among the three steering modes of 1) Ackermann steering, 2) Active-front-and-rear steering, and 3) combination of spinning steering and crab steering to accomplish those tasks effectively. This algorithm includes a four-step optimization strategy for determining the optimal steering mode for different situations. Firstly, it computes the initial and ending postures of the robotic system, and then calculates possible paths connecting both postures for the three steering modes in absence of obstacles and worksite boundaries. In the third step, unsuitable paths are filtered out according to the obstacles and boundaries of worksites. Eventually an optimized path in terms of shortest path length is picked from the rest of admissible paths. The developed path planning algorithm was simulated in the Matlab* *environment to validate its accuracy, and then implemented with a self-propelled robotic platform "bin-dog" system equipped with a 4WIS system in commercial orchard environment to validate its functionalities.*

Keywords. *Path planning, four-wheel-independent-steering system, bin management, apple harvesting*

Introduction

Bin management is an important operation for tree fruit crops during harvesting in tree fruit orchards (Ye et al., 2016). The entire bin management process which is typically completed by tractor-mounted forklifts in orchards includes empty bin placement, half-full bin handling, and full bin transportation. It requires skilled tractor drivers and is high labor intensity due to the long operation time. To mitigate this challenge, auto-steer technology would be a potential solution for bin management using autonomous orchard platforms.

In past decades, as the development of computing units and sensor technologies, auto-steer technology has gained a wide application in agriculture. Numerous studies (O'Connor et al., 1996; Zhang and Qiu, 2004; Roberson and Jordan, 2014) indicated that auto-steer technology is a good answer for labor shortage. Despite of the wide and mature application of auto-steer technology in farm vehicles, only a few researches studied the auto-steered platforms in orchard environment (Freitas et al., 2012; Subramanian and Burks, 2007), which could be attributed to the difficulty in maneuvering in the confined space. An auto-steered system in tree fruit orchards needs to be capable of safely navigating on aisles formed by tree rows and quickly steering into an aisle from orchard headland. Such orchard environment requires the auto-steered system to robustly operate in confined space to avoid damaging fruit trees or hitting bins. Operations such as steering back to center line, steering into an aisle, loading a bin in an aisle without stop, and reverse driving could be quite challenging for equipment with large size or large turning radius. To combat with the challenge of maneuvering in confined space, Witney (1996) and Hunt (2001) described common turning patterns on for car-like vehicle at headlands. Those turning patterns are based on Dubins' curves (Dubins, 1957) or Reeds-Shepp Curves (Reeds and Shepp, 1990). Turning patterns described in their works have been integrated into researches (Hansen et al., 2007; Bochits and Vougioukas, 2008; Bochitis et al., 2009) to minimize non-working travel distance and increase crop coverage.

Bin-dog system is a robotic platform with 4WIS system implementable in typical Washington State tree fruit orchards to improve the bin management efficiency during tree fruit harvesting (Ye et al., 2016). Bin-dog system is able to manage bins (replacing a full bin with an empty bin) in a five-step process: (1) load an empty bin in collection station and drive it into an aisle between tree rows till reaching the full bin; (2) lift the empty bin and drives over the full bin; (3) continue to the target spot and place the empty bin; (4) drive back to load the full bin; and (5) drive the loaded full bin out of the aisle to the collection station. The steering tasks of bin-dog system could be categorized into three major cases: steering back to the center line of two tree rows, steering into an aisle from headland, and loading a bin on an aisle. Comparing to automated equipment applied in open area, automated systems in orchard environment have to tackle with challenging worksite situations. In a typical modern orchard in Pacific Northwest region of U.S., the width of a headland, depending on the design of an orchard, could be up to 6.0 m and down to 3.5 m. Inter-row spacing (trunk to trunk) of two adjacent rows apple trees is typically 2.7 or 3.6 m which are becoming standardized for lots of modern apple orchards. Considering the canopy width of a tree row is about 1.0 m, the effective width of an aisle for operation is no more than 1.7 or 2.6 m. Also the width of a standard bin is only slightly narrower than the available space between tree rows. These factors create quite confined environment and leave limited space for operations of major tasks for bin management such as straight line driving on an aisle, steering into an aisle from headland, and bin-loading on an aisle . Thus to effectively complete above tasks while fully exploit the advantage of 4WIS on maneuverability, optimized steering strategies integrate steering modes as well as turning patterns could provide a solid solution for high effective operations, especially in confined space like orchard environment. The primary goal of this study was to develop a steering strategy selection algorithm to optimize operations in bin management by selecting steering modes and generating their corresponding turning patterns. The result of this study will provide guidelines for designing autonomous navigation controller for robotic platform with 4WIS system in orchard environment.

Materials & Methods

A steering strategy for 4WIS system consists of the application of a turning pattern and its corresponding steering mode in this study. In order to effectively complete a task in orchard environment using a 4WIS system, an algorithm of steering strategy selection needs to consider different steering modes, turning patterns and worksite environment. Thus in the following sections, we will discuss the characteristics of turning patterns and tasks of bin management in detail.

Research platform

A bin-dog research prototype (Fig 1) for bin management in orchard environment was designed and fabricated as a research platform.

Fig 1. Bin-dog prototype with four-wheel-independent-steering

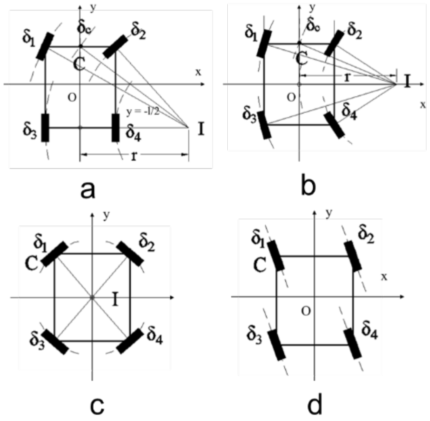


Fig 2. Four steering modes of four-wheel-independent-steering: (a) Ackermann steering, (b) active-front-and-rear-steering, (c) spinning, and (d) crab steering.

To improve the maneuverability of bin-dog system in confined space, bin-dog system adopted a 4WIS system as its steering and driving system. The 4WIS system was made of an electrohydraulic system driven by a 9.7 kW gas engine. 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 Fig 2), were used in this study.

Among those to-be-studied steering modes, when Ackermann or AFRS steering is applied, bin-dog can only move forward or backwards in a direction parallel to the orientation of its heading angle. Even though all the wheels are capable of rotating 180°, to reduce the driving resistance, turning radiuses of Ackermann and AFRS steering are typically lower bounded. In this study, the minimum turning radius of the bin-dog platform are 2.3 and 1.7 m when implementing Ackermann steering and AFRS, respectively. A GPS-based navigation system for this 4WIS system was reported in previous work (Ye et al., 2016). Pure pursuit method was adopted to track desired trajectory for both Ackermann and AFRS steering. Field test showed that bin-dog was able to follow a Lemniscate curve with a mean absolute lateral error of 0.06 and 0.03 m respectively at a longitudinal speed of 0.40 $m \cdot s^{-1}$ using Ackermann and AFRS steering. The instantaneous center of rotation (ICR) of spinning mode locates at the geometry center of bin-dog. Thus spinning can only effectively correct orientation error (namely capable of accomplishing zero radius turning) and is not capable of changing the position of the platform. The orientations of all wheels are the same when crab steering is applied. Thus crab steering can only effectively correct position error (namely capable of accomplishing zero turning repositioning) and is not capable of changing the heading angle of the platform. In order to complete a task, due to the limitation of spinning and crab steering, these two steering modes are often used together with Ackermann or AFRS steering to form a multi-mode steering strategy.

Tasks of bin management

As mentioned, the tasks of bin management could be divided into three different cases. Fig 3 to 5 depicted the schematics of the three cases. In the three figures, an orchard coordinate system (represented by ${}^{o}x{}^{o}O{}^{o}y$) was defined as global coordinate system for these three tasks. Its x-axis is parallel to headland while its y-axis is parallel to an aisle. The origin of orchard coordinate system is set at the middle point of the entrance of the aisle. Bin-dog coordinate system (represented by ${}^{v}x{}^{v}O{}^{v}y$) moves with bin-dog. It is used to illustrate the pose of bin-dog. Its x-axis and y-axis point to longitudinal and lateral direction of bin-dog frame respectively. The origin of bin-dog coordinate system locates at the geometry center of bin-dog. The bin coordinate system (represented by ${}^{b}x{}^{b}O{}^{b}y$) is used to illustrate the pose of a bin. Its x-axis and y-axis point to longitudinal and lateral direction of the frame of the bin respectively. The origin of bin coordinate system locates at the geometry center of the bin.

Fig 3 illustrates the task of steering back to center line of an aisle, bin-dog with distance offset d_g (distance between the geometry center P_g of bin-dog to the center line of the aisle) and heading angel ϕ_g is represented by a rectangle. Two bolded lines on two sides represent the tree walls. The tracking point of bin-dog (it locates at the middle point of two rear wheels for Ackermann steering and geometry center for AFRS, spinning and crab steering) is P_t. In this task, bin-dog follows a path to drive back to center line of the aisle and correct its orientation error. Fig 4 illustrates the task of steering into an aisle from the headland. The goal of this task is to drive the bin-dog from headline to reach the center line of an aisle. In the figure, a headland width is H and a tree lane with inter-row spacing is W. Bin-dog initially parks at the headland with heading parallel to the direction of headland (heading angle ϕ_g of -90°). The distances from the geometry center P_g to the center line of the aisle and left side of headland are d_g and h respectively. Fig 5 illustrates the case of bin loading. The goal for this task is to align bin-dog with a bin without stop or reversing between the tree rows. In the figure, bin-dog is represented by a magenta rectangle with distance offset of d_{g1} and heading angel of ϕ_{g1}. A bin is represented by a blue square with distance offset (distance from geometry center of the bin B_g to center line of tree lane) of d_{g2} and heading angle of ϕ_{g2}. The distances from P_g and B_g to x-axis of orchard coordinate system is h_{g1} and h_{g2} respectively. As in this task bin-dog is supposed to align with the bin instead of tree rows, the offset error d should be defined as the distance from the tracking point of bin-dog to the y-axis of bin coordinate system, and orientation error is the angle between heading vector of bin-dog and y-axis of bin coordinate system which equals to ϕ_{g1}-ϕ_{g2}.

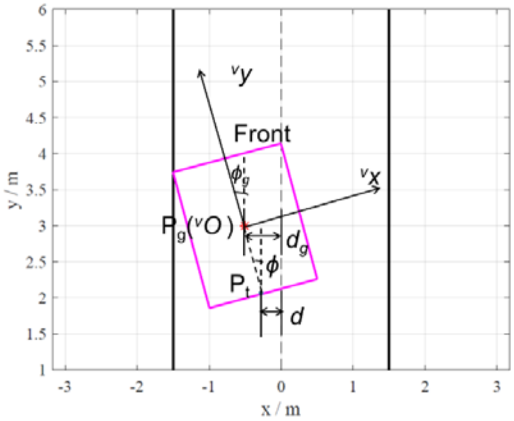


Fig 3. Schematic for steering back to center line.

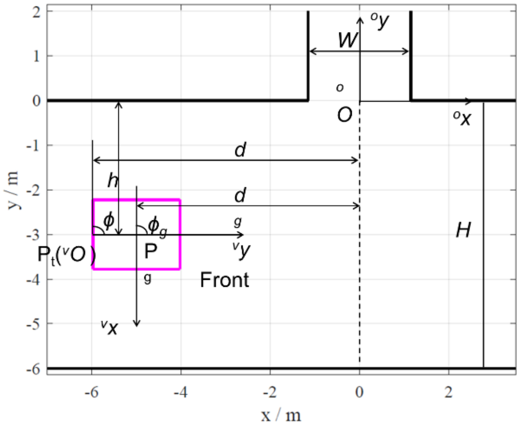


Fig 4. Schematic of the coordinate systems defined for a bin-dog steering into an aisle from the headland.

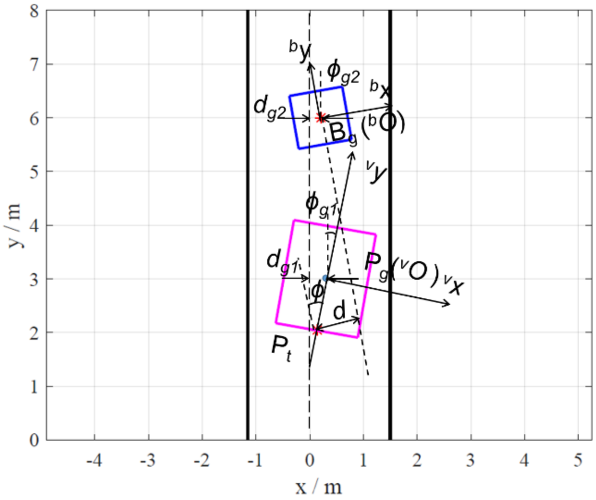
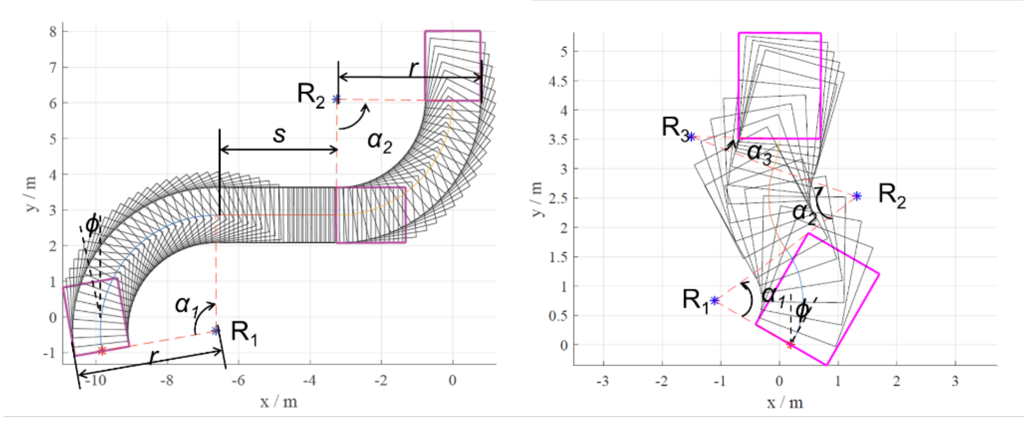


Fig 5. Schematic of the coordinate systems defined for a bin-dog performing bin-loading operations within an aisle.

Turning patterns

Turning patterns for Ackermann and AFRS steering

Turning patterns are paths connecting initial pose (includes position and orientation) and final pose. As shown in Fig 6a, a wheeled robot could follow a turning pattern which is consisted of a sequence of circular arcs and straight line segments to reach final pose from its initial pose. The design of such turning patterns are restricted by physical constraints such as minimum turning radius, available steering modes of the robot and environment constraints such as inaccessible boundaries or obstacles. Dubins' curve is a common approach to generate turning patterns for car-like robot. Based on Dubins' theorem (Dubin, 1957), for a robot moving forwards on an empty plane with minimum turning radius *r*, the shortest path between any two poses falls into one of the following six types of patterns: *LSL*, *LSR*, *RSL*, *RSR*, *LRL*, and *RLR*, where *L* represents left turn, *R* represents right turn, and *S* represents straight driving. These six possible turning patterns can be divided into two groups. The first group includes configurations of *LSR*, *RSL*, *RSR*, and *LSL*. As shown in Fig 6a, the path for first group turning patterns starts with an arc (turning with an angle of α_1 and radius of *r*), followed by a straight line (length of *s*), and ends with another arc (turning with an angle of α_2 and radius of *r*). α_1 or α_2 is positive if the robot turns left and negative when turns right. The other group includes configurations of *LRL* and *RLR* which consist of three successive arcs (Fig 6b). The combination of the three variables determines a unique turning pattern.



(a) (b)

Fig 6. An illustration of Dubins' curves for (a) a Right-Straight-Left turning pattern, and (b) a Left-Right-Left turning pattern.

If the initial location ([*d*,0,1]) and pose errors of the tracking point are known (*d* and ϕ), the final location of the track point after following a Dubins' curve of the two groups could be calculated using equations below:

$$ {}^{t}P = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} d - s \cdot \sin(\phi + \alpha_1) + r_1 \cos\phi - r_1 cos(\phi + \alpha_1) + r_2 cos(\phi + \alpha_1) - r_2 \cos(\phi + \alpha_1 + \alpha_2) \\ s \cdot \cos(\phi + \alpha_1) + r_1 \sin\phi - r_1 sin(\phi + \alpha_1) + r_2 sin(\phi + \alpha_1) - r_2 \sin(\phi + \alpha_1 + \alpha_2) \\ 1 \end{bmatrix} \quad (1) $$

$$ {}^{t}P = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} d + r_1 \cos\phi + (r_2 - r_1) cos(\phi + \alpha_1) + (r_3 - r_2)\cos(\phi + \alpha_1 + \alpha_2) - r_3 \cos(\phi + \alpha_1 + \alpha_2 + \alpha_3) \\ r_1 \sin\phi + (r_2 - r_1) sin(\phi + \alpha_1) + (r_3 - r_2)\sin(\phi + \alpha_1 + \alpha_2) - r_3 \sin(\phi + \alpha_1 + \alpha_2 + \alpha_3) \\ 1 \end{bmatrix} \quad (2) $$

As there are six possible types of turning patterns, the final location could be simplified into six different forms. Furthermore, as the three successive transformations are expected to remove offset error and orientation error, thus the values of variables α_1, α_2 and s/α_3 should be selected to satisfy the following constraint equations:

For both groups: $$x = 0 \quad (3)$$

For group 1: $$\alpha_1 + \alpha_2 + \phi = 0 \quad (4)$$

For group 2: $$\alpha_1 + \alpha_2 + \alpha_3 + \phi = 0 \quad (5)$$

Multiple forms (with different variable configuration) of turning patterns may be possible to complete the bin management tasks. In order to find a turning pattern to effectively complete above mentioned tasks, in this study, we define an optimized turning pattern to have shortest total travel distance T_s (total travel distance on tracking point). In order to find an optimized turning pattern, we firstly calculate the optimized turning pattern of each type. Such calculation were solved using function *fmincon* provided by optimization toolbox from Matlab. The calculation could also determine the feasibility of a type turning pattern. Feasible turning patterns are turning patterns that are theoretical achievable when boundaries are not considered. If no solution was found for a certain type of turning pattern, it will not be possible for bin-dog to follow this type of turning pattern to complete the task. Once all the optimized turning patterns for the six types were calculated, the optimized turning pattern for the algorithm could be determined by selecting the turning pattern with shortest T_s from the six types.

Turning pattern for multi-mode

Steering strategy with multi-mode completes a task with multiple steering modes. For multi-mode, its turning pattern is designed in a way that firstly Ackermann steering will be used to get close to targeted point. Then spinning is used to correct orientation error, and/or crab steering will be used to correct position error. Eventually, Ackermann steering is used again to approach to the target.

Steering strategy selection algorithm

A steering strategy selection algorithm for bin management can be illustrated using a flowchart in Fig 7. For simplicity, the representation of a steering strategy could be abbreviated in a form of turning patterns-steering mode. For example, LRL-AKMN is a steering strategy with Ackermann steering mode in *LRL* turning pattern.

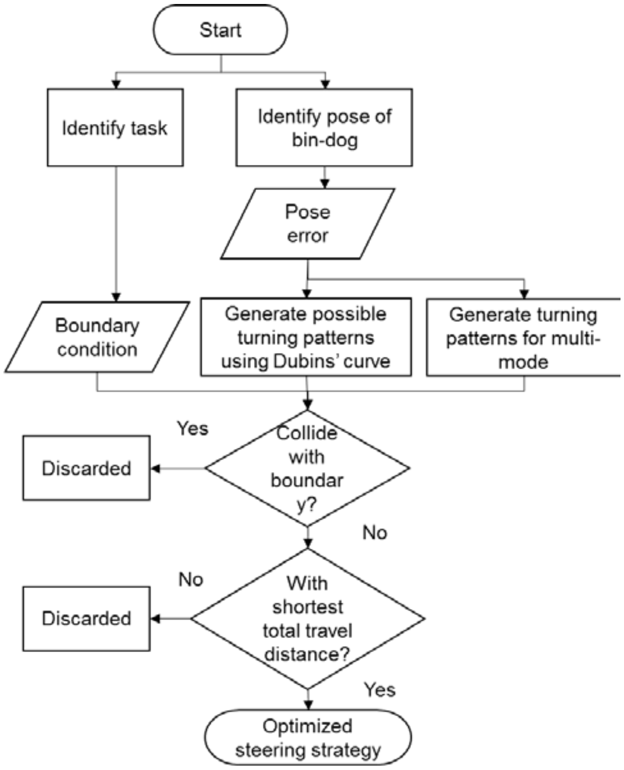


Fig 7. Flowchart for steering strategy selection algorithm for bin management.

The algorithm is mainly consisted of five steps:

1. Identify pose of bin-dog (distance offset and heading angle), establish coordinate systems and calculate pose errors. The pose of bin-dog is assumed to be a known input for this algorithm. Then the pose errors could be calculated based on the worksite environment discussed in previous section.
2. Calculate feasible Dubins' curves for Ackermann and AFRS steering based on their minimum turning radius and the pose errors identified in first step. In this step, feasible Dubins' curves are determined through two steps: (i) determine function of T_s, range of variables, and constraint equations based on minimum turning radius and pose errors for all six types of turning patterns; (ii) test the feasibilities of all six types, calculate the values of variables which minimizes corresponding T_s, and calculate T_s for optimized turning patterns of each feasible type using function *fmincon*.
3. Determine turning patterns for multi-mode. Turning patterns using multi-mode are specifically calculated for each case. In general, such a turning pattern designed so that the orientation error will be removed using spinning, and position error will be removed by crab steering. Ackermann steering is also required to track straight paths.
4. Filter unsuitable turning patterns with could result in collision with boundaries of worksite or bin. Steps 2 and 3 find feasible turning patterns without considering boundaries. Based on the coordinates of feasible turning, the theoretical locations of the frame of bin-dog on the turning pattern could also be determined. By examine locations of the frame of bin-dog and boundaries conditions, turning patterns which result in collision could be found.
5. Find best steering strategy with shortest total travel distance from the rest of turning patterns.

Field tests

In order to validate the proposed steering strategy selection algorithm, a set of field tests for each tasks was conducted in a commercial orchard (Fig 8) in Prosser, WA. The tree architecture in this orchard is V-trellis fruiting wall with the inter-row spacing (trunk to trunk) of 3.6 m. The space narrows to 2.3 m at the height of 1.5 m. The width of the headland is 6.0 m.

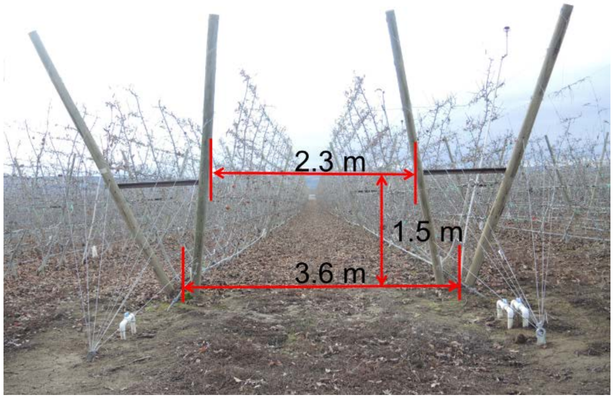


Fig 8. Orchard for field test

In the first set tests, the steering strategy selection algorithm was validated for steering back to centerline with a bin-dog pose configuration (20° heading angle with 0 m distance offset). The setup of the experiments is illustrated using Fig 9. The initial location of geometry center of bin-dog P_g was set at [0; 3; 1]. If using Ackermann or AFRS steering, bin-dog firstly corrected its pose error using Dubins' curve, and then kept tracking the straight line till point B [0; 8; 1]. If multi-mode is used, bin-dog firstly span clockwise till its heading angle was 0°, then switched into Ackermann steering afterwards to track the straight line till it reached point B. In the second set tests (Fig 10), steering strategy selection algorithm was validated for steering into an aisle from headland at a designed location (h = -3 m with d_g = -5 m). For Ackermann or AFRS steering, bin-dog firstly parked at headland with its geometry center located at [-5; -3; 1]. It then entered the aisle using different turning patterns till it reached point B [0; 4; 1]. For multi-mode, spinning combined with Ackermann steering was used. Bin-dog used Ackermann steering to track the straight line till P_g was close to point C [0; -3; 1]. Afterwards it switched into spinning and rotated 90°, and then back to Ackermann steering to track line CB till it reached point B. In the third set tests (Fig 11), steering strategy selection algorithm was validated for bin-loading in an aisle. As shown in Figure 11, a designed bin and bin-dog location configuration (ϕ_{g1} = 0°, ϕ_{g2} = 10°, d_{g1} = 0 m, d_{g2} = -0.18 m, h_{g1} = 3, h_{g2} = 7 m) was tested on the aisle. If using Ackermann or AFRS steering, bin-dog was guided to align with the bin from P_g [0; 3; 1] using Dubins' curves. If using multi-mode, bin-dog started at P_g, firstly Ackermann steering was used to track straight line till it reached point B [0; 4; 1]. Then bin-dog switched into spinning to rotate counter-clockwise till its heading angle is 10°, and followed by crab steering until reached point C [0.18; 5; 1] (on the center line of the bin). Finally, bin-dog kept driving forward till it engaged with the bin at point D [0; 6; 1].

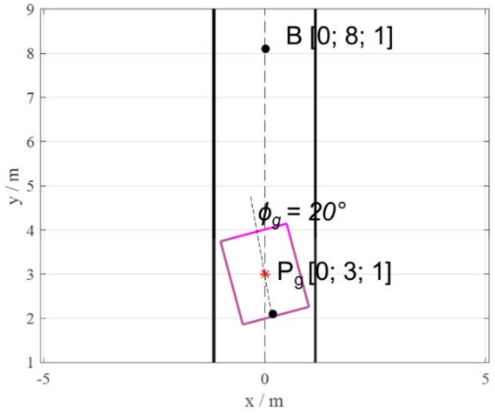


Fig 9. Experiment setup for steering back to center line.

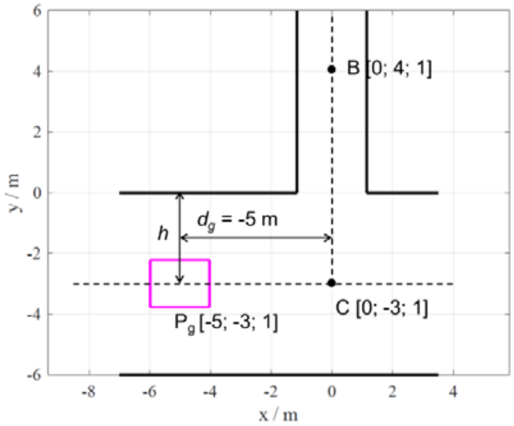


Fig 10. Experiment setup for steering into an aisle.

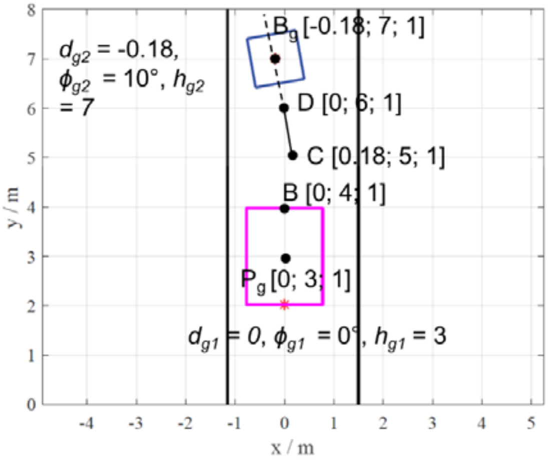


Fig 11. Experiment setup for bin loading.

Before field tests, simulation was conducted for each task to determine feasible and optimized steering strategies to achieve the particular tasks, and Table 1 lists the simulation results for all the tasks.

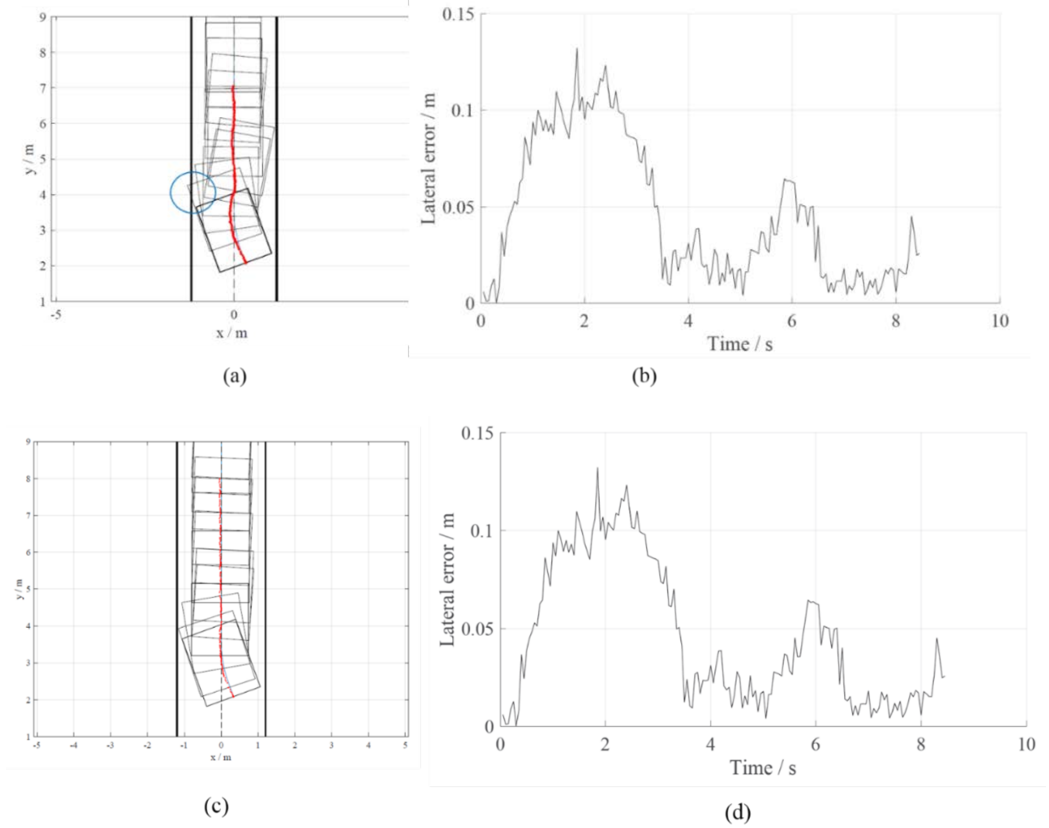
Table 1. Simulation results for all the three tasks.

Task #	Steering modes	Feasible turning patterns	Collision	Variables	Theoretical total travel distance (m)	Optimized steering strategy
1	AKMN	LSR/RLR	Yes	α_1 = 3.3°, α_2 = -23.3°, s = 0	5.01	RSL/LRL-AFRS
		RSR	Yes	α_1 = 0°, α_2 = -20.0°, s = 0.40	5.03	
	AFRS	RSL/LRL	No	α_1 = 0°, α_2 = -34.1°, α_3 = 14.1°	5.00	
	MULTI	SPIN+AKMN	No	/	5.34	
2	AKMN	LRL	No	α_1 = 0°, α_2 = -17.1°, α_3 = 107.1°	10.70	LRL-AKMN
		LSL/RSL	Yes	α_1 = 0°, α_2 = 90°, s = 2.22	10.34	
	AFRS	LRL	No	α_1 = 0°, α_2 = -33.4°, α_3 = 123.4°	11.91	
		LSL/RSL	No	α_1 = 0°, α_2 = 90°, s = 2.62	10.99	
	MULTI	SPIN+AKMN	No			
3	AKMN	LRL/RSL	Yes	α_1 = 0°, α_2 = -17.7°, α_3 = 27.7°	2.43	MULTI
		LSL	Yes	α_1 = 0°, α_2 = 10°, s = 3.67	4.23	
	AFRS	LRL/RSL	Yes	α_1 = 0°, α_2 = -17.9°, α_3 = 27.9°	1.90	
		LSL	Tree	α_1 = 0°, α_2 = 10°, s = 2.78	3.17	
	MULTI	SPIN+CRAB+AKMN	No	/	3.19	

In the table, tasks 1 to 3 are steering back to center line of an aisle, steering into an aisle from headland, and bin loading respectively. LSR/RLR under feasible turning patterns indicated that when turning patterns of LSR and RLR has the some common formats (for LSR, $s = 0$; for RLR, $\alpha_3 = 0$). Collision column marked whether bin-dog would collide with trees or bin when implementing a steering strategy in simulation. For the first task, all feasible turning patterns were tested. If a turning pattern would collide with trees, it was tested in open area. For the second task, turning patterns which will not collide with trees were tested. For the third task, due to the limited space, when the bin had a heading angle of 10°, it was quite difficult for Ackermann or AFRS steering mode to align with the bin on an aisle. Thus to validate the algorithm, only multi-mode was tested on an aisle, and steering strategies LRL-AKMN and LRL-AFRS were tested in open area.

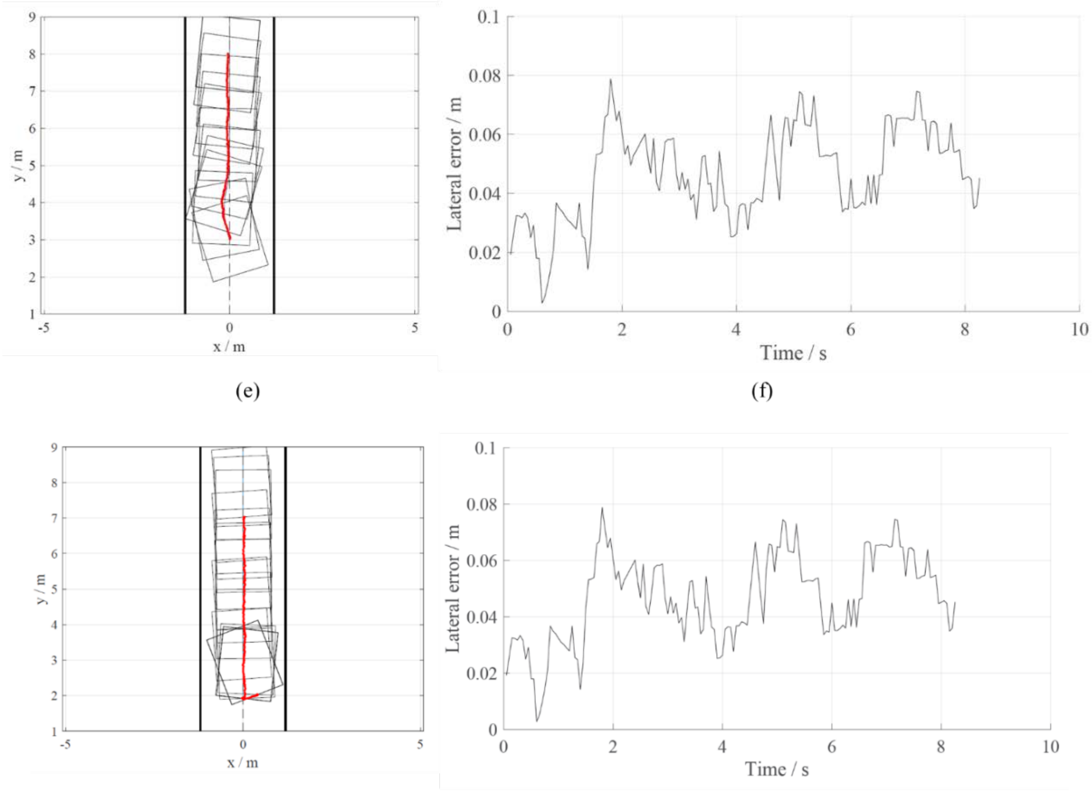
Results & Discussions

Fig 12 illustrated the result of correcting 20° orientation error and steering back to center line using different steering strategies. When using Ackermann steering, two feasible turning patterns *LSR* and *RSR* could be used to steer bin-dog back to the center line when no boundary was considered. However, the frame of bin-dog would collide with tree row on left side if these two turning patterns are adopted. For AFRS steering, only turning pattern *RSL* was available and it could be used without hitting any tree row. For multi-mode, the orientation error was quickly corrected using spinning mode and it required the least space for operation.



(a) (b)

(c) (d)



(e) (f)

(g) (h)

Fig 12. Result for steering back to center line with orientation error: (a) Correction using turning pattern Right-Straight-Left with Ackermann steering; (b) lateral error of (a); (c) correction using turning pattern Left-Straight-Left with Ackermann steering; (d) lateral error of (c); (e) correction using turning pattern Right-Straight-Left with active-front-and-rear-steering; (f) lateral error of (e); (g) correction with multi-mode; (h) lateral error of (g).

Comparing to Ackermann steering, smaller turning radius of AFRS mode allowed it to complete turning patterns in small space even with large initial pose error. Multi-mode with spinning was effectively to remove orientation error and had least spatial requirement. But the stops (each stop took 1 s for current configuration) for spinning limited its performance in terms of work efficiency. Multi-mode with crab steering was effectively to remove position error and it can smoothly switch into other steering modes.

Fig 13 illustrated results of completing tasks of steering into an aisle from headland using different steering strategies. As indicated by Fig 13 (a), (c), (e) and (g), the four steering strategies (LRL-AKMN, LRL-AFRS, LSL-AFRS and multi-mode) could achieve collision-free correction for this task. The field test results validated the simulation results in Table 1. Fig 13 (b), (d), (f) and (h) show the lateral errors during the four corrections. The mean absolute lateral errors for LRL-AKMN, LRL-AFRS, LSL-AFRS and multi-mode were 0.04±0.02, 0.02±0.01, 0.01±0.01, and 0.02±0.01 m respectively which were acceptable for the task. The large error spike in Fig 13 (d) was caused by the spinning. Correction using spinning was achieved by carefully rotating bin-dog to the targeted heading angle without any predesigned path. The big error in Fig 13 (d) caused by the change of bin-dog control point during spinning, which did not result in lateral error and could be ignored in the error calculation. Therefore, when calculating mean absolute lateral error for multi-mode, this segment was removed before calculating mean absolute lateral error for multi-mode.

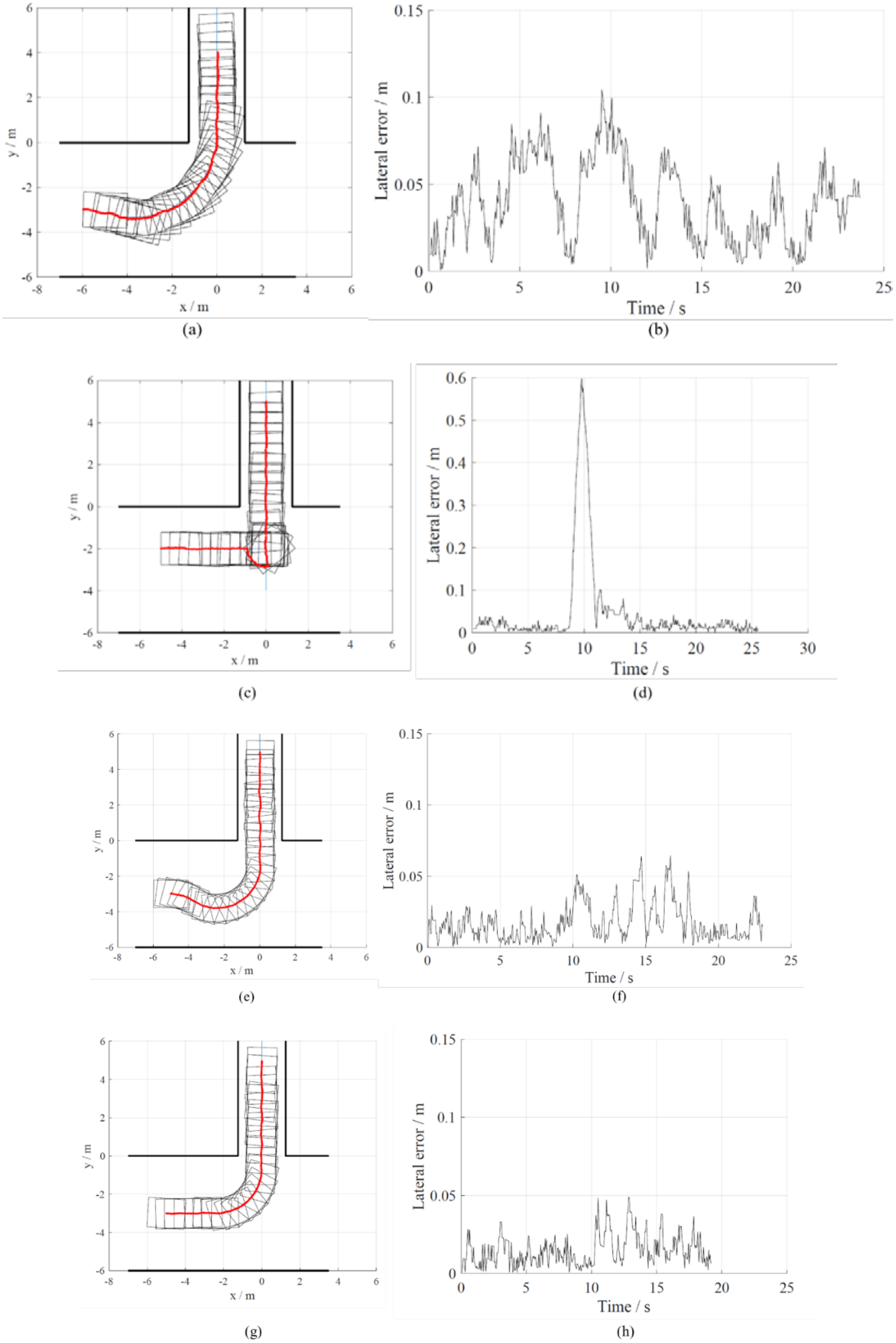
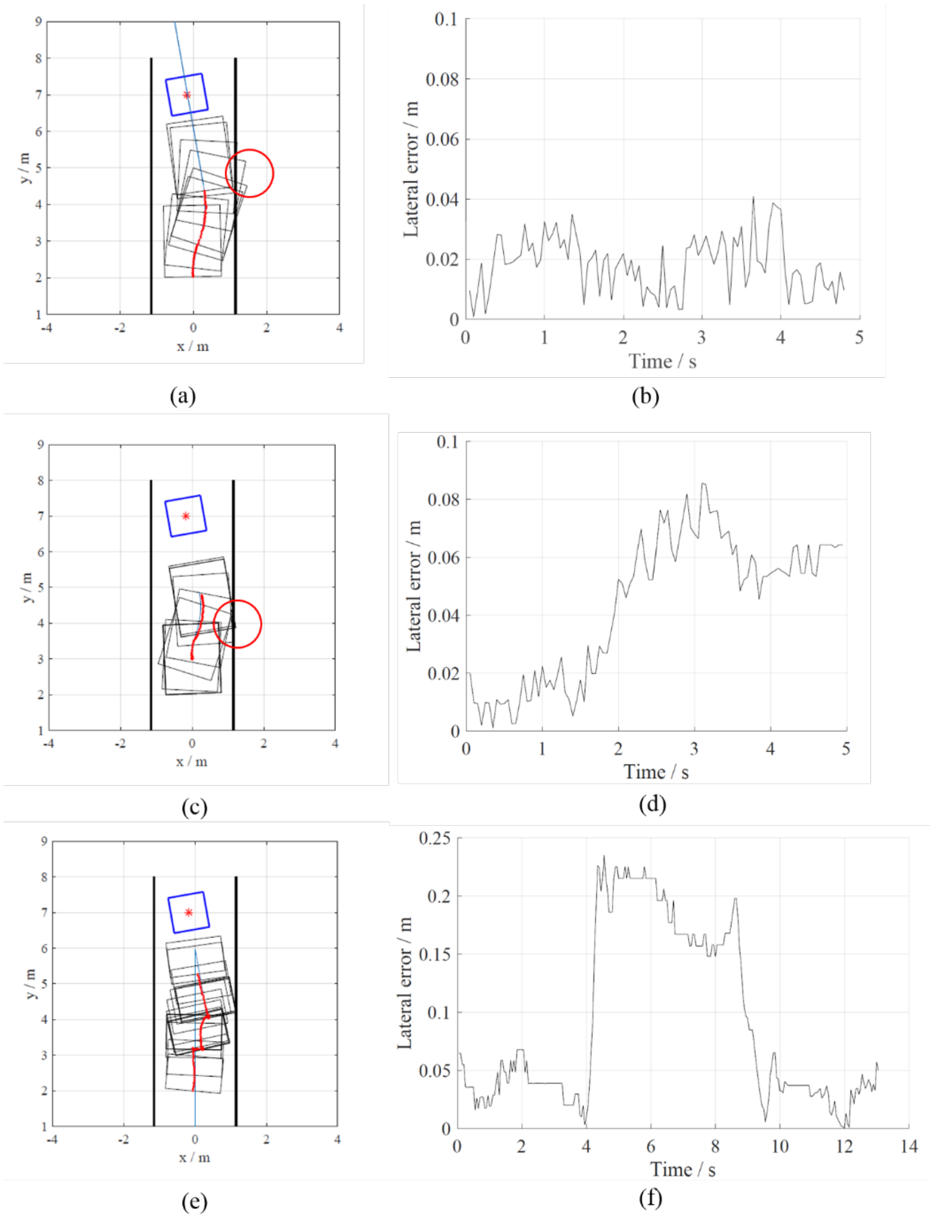


Fig 13. Test result for steering into an aisle: (a) correction using Right-Straight-Left turning pattern with Ackermann steering; (b) lateral error of (a); (c) correction using multi-mode; (d) lateral error of (c); (e) correction using Right-Straight-Left turning pattern with active-front-and-rear-steering; (f) lateral error of (e); (g) correction using Left-Straight-Left turning pattern with active-front-and-rear-steering; (h) lateral error of (g).

Fig 14 illustrated results of bin-loading tests using three steering strategies. As indicated by Fig 14 (a), (c), and (e), for all the three steering strategies, only multi-mode could achieve collision-free correction which validated the simulation results in Table 1. In this test, both Ackermann and AFRS steering could not be used to align with the bin without hitting trees on an aisle. An open space test was conducted for these two steering strategies. The mean absolute lateral errors for RSL-AKMN, RSL-AFRS and multi-mode were 0.02±0.01, 0.03±0.02 and 0.03±0.02 m respectively. Table 2 listed the detail results of all the tests. Similar to previous tests, no path was designed for crab steering and spinning. Thus the mean error for multi-mode was calculated only for straight path tracking. Tests in open area revealed that AFRS required smaller space to align with the bin than Ackermann. In summary, when a bin was place on an aisle with orientation error, aligning bin-dog with the bin using only Ackermann or AFRS steering could be quite challenging, and by carefully design a steering strategy for multi-mode, it was possible to for bin-dog complete the task in such a confined space without hitting the bin or trees. However as shown in Fig 14a and 14b, results in open area still suggest that bin-dog could well align with the bin if the aisle was wider or bin-dog had a smaller size.



(a) (b)

(c) (d)

(e) (f)

Fig 14. Test results for bin-loading on and aisle: (a) correction using Right-Straight-Left turning pattern with Ackermann steering; (b) lateral error of (a); (c) correction using Right-Straight-left turning pattern with active-front-and-rear-steering; (d) lateral error of (c); (e) correction using multi-mode; (f) lateral error of (e).

Table 2. Field test results for the three tasks.

Task #	Steering modes	Feasible turning patterns	Collision	ABSE±STD	RMSE	Actual total travel distance (m)	Best steering strategy
1	AKMN	LSR/RLR	Yes	0.05±0.04	0.06	5.69	RSL/LRL-AFRS
		RSR	Yes	0.02±0.02	0.03	5.36	
	AFRS	RSL/LRL	No	0.05±0.02	0.05	5.16	
	MULTI	SPIN+AKMN	No	0.03±0.01	0.04	5.35	
2	AKMN	LRL	No	0.04±0.02	0.05	12.87	LSL/RSL-AFRS
		LSL/RSL	Yes	/	/	/	
	AFRS	LRL	No	0.02±0.01	0.02	13.78	
		LSL/RSL	No	0.01±0.01	0.02	12.32	
	MULTI	SPIN+AKMN	No	0.02±0.01	0.02	14.68	
3	AKMN	LRL/RSL	Yes	0.02±0.01	0.02	2.59	MULTI
		LSL	Yes	/	/	/	
	AFRS	LRL/RSL	Yes	0.03±0.02	0.05	2.37	
		LSL	Tree	/	/	/	
	MULTI	SPIN+CRAB+AKMN	No	0.03±0.02	0.03	4.61	

In Table 2, ABSE is the mean absolute error; STD is the standard deviation; RMSE is the root mean square error; best steering strategy is the steering strategy which had minimum actual total travel distance. The best steering strategy for task 1 was the same with the optimized steering strategy selected by the algorithm. However, it was different in task 2. The actual total travel distance could be influenced by the path tracking performance. If the path tracking had too much oscillation, the actual total travel distances could be longer than theoretical values. The actual total travel distances could also be shorter than theoretical values if the platform took "shortcuts" and did not precisely follow the path. Thus the best steering strategy may disagree with the selection of the algorithm when the theoretical total travel distances of several feasible collision-free steering strategies were similar. In the case of task 2, the optimized steering strategy was LRL-AKMN while the best steering strategy in field test was LSL/RSL-AFRS. Comparing to the task of steering back to the center line of aisle, the theoretical total travel distances in this task were longer which had more opportunities of oscillation and shortcuts during the path tracking. Thus the optimized steering strategy could disagree with the best steering strategy from actual tests.

Conclusion

In this paper, a steering strategy selection algorithm was developed based on the discussion of characteristics of steering modes, tasks of bin management and turning patterns of different steering modes. Field tests of the three major tasks were designed to validate the algorithm in orchard environment. The major conclusions of this study were the following:

- Validation tests proved the developed algorithm could be used to complete tasks including steering back to center line of an aisle, steering into an aisle from headland, and loading a bin on an aisle in real orchard environment. The algorithm was able to generate applicable steering strategies, correctly determine whether a steering strategy would lead to collision with boundaries of worksite, and select an optimized steering strategy which was collision-free and had shortest theoretical total travel distance.
- The best steering strategy which had the shortest actual total travel distance in field tests may disagree with the selection of the algorithm. The mismatch was mainly due to the influence of path tracking performance. The actual total travel distances could be longer than theoretical values if the path tracking was oscillatory. The actual total travel distances could also be shorter than theoretical values if the platform took "shortcuts" and did not precisely follow the path.
- Bin-dog could follow turning patterns generated by the algorithm using both Ackermann and AFRS steering to correct pose errors with satisfactory accuracy (mean absolute lateral error less than 0.05 m) at a speed of 0.40 m·s^{-1}. The accuracy was sufficient for bin-dog to complete

the three major tasks.

- In all the three tasks, AFRS showed smaller space requirement comparing to Ackermann steering due to its small turning radius. Multi-mode which had the least space requirement was effective to remove orientation or position error in the three tasks.

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