Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

ELSEVIER

Biosystems ENGINEERING

Research Paper

Orchard manoeuvring strategy for a robotic bin-handling machine

Yunxiang Ye [a], Long He [a], Zhaodong Wang [c], Dylan Jones [b], Geoffrey A. Hollinger [b], Matthew E. Taylor [a,c], Qin Zhang [a,*]

[a] The Center for Precision and Automated Agricultural Systems, Washington State University, Prosser, WA, 99350, USA

[b] School of Mechanical, Industrial & Manufacturing Engineering Oregon State University, Corvallis, OR, 97331, USA

[c] School of Electrical Engineering & Computer Science, Washington State University, Pullman, WA, 99164, USA

ARTICLE INFO

Article history:
Received 19 December 2016
Received in revised form
13 November 2017
Accepted 13 December 2017

Keywords:
Automatic navigation
Four-wheel-independent-steering system
Bin management
Tree fruit

Unlike a car-like vehicle manoeuvring its way in an open field, a four-wheel-independent-steered robotic machine placed in an orchard must operate in a very confined working space between tree rows. Because the machine is subject to the unique constraints of the worksite space and operation limits, multiple steering modes are often required to effectively accomplish the desired bin-handling manoeuvers. In this study, we created a multi-mode manoeuvring strategy selection method to generate strategies that can guide the robotic platform to accomplish bin handling tasks, such as correcting pose error between tree rows, entering a tree lane from the headland, and loading a bin between tree rows, effectively. The method determines the manoeuvring strategies based on the situation among four steering modes: 1) Ackermann steering, 2) coordinated four wheel steering, 3) crab steering, and 4) spinning. The study first evaluated applicable strategies and selected the best of these strategies for different bin handling scenarios. Then, the selected strategies were implemented to drive a four-wheel-independent-steering (4WIS) system to complete the tasks in a commercial orchard in order to validate the method. Obtained results showed that the system could navigate the platform on desired trajectories to complete bin-handling tasks with a root mean square errors less than 0.06 m.

1. Introduction

Bin handling is an important operation in tree fruit harvesting (Ye, He, & Zhang, 2017). The traditional bin handling process, including empty bin placement, half-full bin repositioning, and full bin removal, is typically completed using human-driven tractor-mounted forklifts in orchards. The operation requires tractor drivers to constantly monitor the status of all bins that are being filled during harvest and handle bins in a confined environment in between tree walls. This process relies heavily on skilled tractor drivers and is highly labour-intensive. To mitigate the challenges, robotic bin-handling machines that navigate via autonomous navigation technology are a potential solution for more efficient harvesting operations.

* *Corresponding author.*
E-mail address: qinzhang@wsu.edu (Q. Zhang).

https://doi.org/10.1016/j.biosystemseng.2017.12.005

Nomenclature

$\alpha_1, \alpha_2, \alpha_3$	Angles of arcs of Dubins' curve
$\alpha_1^*, \alpha_2^*, \alpha_3^*$	Angles of the arcs of the shortest Dubins' curve
θ	Angle of rotation
ϕ	Orientation error
ϕ_g	Heading angle of the bin-handling machine
δ_{ai}	Actual steering angle of the ith wheel
δ_c	Desired steering angle
δ_{di}	Desired steering angle of the ith wheel
d	Position error
d_g	Distance offset
$e_{\delta i}$	Error of wheel angle
e_{ld}	Distance from a goal point to the heading vector of the vehicle
e_{vi}	Error of wheel speed
e_p	Posture error
g_x, g_y	Coordinates of a goal point
L	Wheelbase of the bin-handling machine
l_d	Look-ahead distance
m	Steering mode
p_a	Actual pose
p_d	Desired path
P_g	Location of geometric centre of the bin-handling machine
P_o	Initial location of the tracking point
P_t	Location of the control point of the bin-handling machine
r	Radius of the arc of the Dubins' curve
r_1, r_2, r_3	x coordinates of the ICR of the machine under the vehicle coordinate system
R_x, R_y	Coordinates of the centre of rotation
s	Length of the straight line of Dubins' curve
Ti	The ith transformation matrix
T_r	Matrix of rotation
T_t	Matrix of translation
v	Vehicle speed
v_{di}	Desired speed of the ith wheel
v_{ai}	Actual speed of the ith wheel
x_c, y_c	Current coordinate of the control point
x_e, y_e	Coordinates of the path marker to end crab steering
X_{ij}	The jth global coordinate of ith corner of the bin-handling machine
g (superscript)	Coordinates under the global coordinate system
o (superscript)	Coordinates under the orchard coordinate system
v (superscript)	Coordinates under the vehicle coordinate system

In past decades, autonomous navigation technology, powered by computing and sensing technology developments, has gained wide application in agriculture. Numerous studies (Roberson & Jordan, 2014; Zhang & Qiu, 2004) have shown that autonomous navigation technology is a good solution for solving skilled labour shortages, high labour costs, and labour-intensive work problems. Despite the wide and mature application of autonomous navigation technology on mobile agricultural machinery, it has limited applications in orchard operations. Barawid, Mizushima, Ishii, and Noguchi (2007) developed an autonomous navigation system using a 2D laser scanner to navigate a tractor between tree rows, and achieved an accuracy of 0.19 m mean lateral error at a speed of 0.36 m s^{-1}. Subramanian and Burks (2007) used multiple sensors including a video camera, a laser scanner, and an inertial measurement unit (IMU) to navigate a two-wheel-steered vehicle in a citrus orchard. They used a laser-based navigation system to navigate along alleyways, and used a vision and laser scanner for headland navigation to guide the vehicle performing simple orchard traversal tasks including straight line tracking between tree rows and alleyway entry.

Few automated machines have been developed to complete more complicated or space-dependent tasks, such as bin handling, for tree fruit production. One reason for the limited applications could be attributed to the difficulty of manoeuvring platforms effectively in a confined space. Figures 1 and 2 show the layout of a modern orchard in the Pacific Northwest region of the U.S. In Fig. 1, the tree rows are planted north–south. They terminate at headlands showed in Fig. 2, which allows equipment to transition among different rows. The width of a headland is normally 3.5–6.0 m, and the effective width of an alleyway is 1.7–2.6 m. Furthermore, the size of a standard fruit bin is about 1.2 m, only slightly narrower than the alleyway. This creates a confined environment and leaves limited space for manoeuvring bin-handling machinery.

Automated bin handling in orchards would need to reliably steer into an alleyway from headland, navigate in the alleyway, and carry-in and remove-out a bin to or from the alleyway. This requires the navigation system to robustly guide the machinery operating in the confined space without damaging fruit trees or hitting bins. To combat the challenge of manoeuvring in a confined space, Witney (1996) and Hunt

Fig. 1 – Overhead view of an orchard.