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Research Paper

Orchard worker localisation relative to a vehicle using radio ranging and trilateration

Stavros G. Vougioukas[*], *Long He*, *Rajkishan Arikapudi*

University of California, Davis, Department of Biological and Agricultural Engineering, One Shields Avenue, Davis, CA 95616-5270, USA

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Safe navigation of labour-aiding robots in commercial orchards will rely on accurate and continuous worker localisation. In this work, an ultra-wideband radio-based system localises a worker via trilateration of four range measurements between antennas on a vehicle and an antenna carried on the worker's belt. Performance results are presented from measurements inside 'work zones' around the vehicle, in open space and in an orchard. At walking speed in open space, when body placement allowed full line-of-sight (LOS) between belt and vehicle antennas, position estimate availability was 99.7% and the distance root mean square error (DRMS) was 57.9 cm. Completely blocked LOS resulted in signal outages and unacceptable performance (11.1% availability; 819.7 cm DRMS). In the orchard, full-LOS performance was similar to that in open-space: 99.3% availability and 63.4 cm DRMS error bound. Orchard trees enabled multipath signal propagation, so blocked-LOS performance was far better than in open-space (60.2% availability; 123.6 cm DRMS). Antenna motion effects were studied in open-space and orchard experiments without body interference. Motion introduced non-collocation errors (individual ranges measured at slightly different positions); DRMS error in open space and orchard were 1.6 and 2.2 times larger than respective static errors. In all experiments the 95th percentiles of the errors were almost twice as large as the DRMS errors. Sporadic large errors and signal outages could be addressed by two belt antennas and filtering. The results indicate that radio ranging offers a practicable approach to orchard worker localisation relative to a nearby vehicle operating at slow walking speeds.

1. Introduction

Orchard operations like spraying, pruning, thinning, mowing, and especially harvesting require intensive manual labour, which contributes significantly to fruit production cost. For example, manual harvesting for apples and sweet cherries accounts for approximately 30% and 50% of production costs respectively (Bull, 2011). Meanwhile, labour availability has decreased in recent years (Hertz & Zahniser, 2013). The combination of high labour cost and labour shortage is a key driver towards the development and adoption of automation technologies that increase the productivity of orchard operations.

* *Corresponding author.*
E-mail address: svougioukas@ucdavis.edu (S.G. Vougioukas).

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Nomenclature

ABSEx	mean absolute error parallel to vehicle frame x-axis
ABSEy	mean absolute error parallel to vehicle frame y-axis
B_i	ith vehicle radio beacon ($i = 1, 2, 3, 4$)
B_m	mobile radio beacon
d_i	true distance between B_i and B_m
DRMS	horizontal distance root mean square position estimation error
e_x	position estimation error parallel to vehicle frame x-axis
e_y	position estimation error parallel to vehicle frame y-axis
e_{xy}	horizontal position estimation error
GPSv	real time kinematic (RTK) GPS on vehicle
GPSm	real time kinematic (RTK) GPS mobile; carried with mobile radio
LOS	line of sight
$O_v(x_v, y_v, z_v)$	vehicle coordinate system
$O_g(x_g, y_g, z_g)$	GPSv coordinate system
$O_{ts}(x_{ts}, y_{ts}, z_{ts})$	total station coordinate system
${}^{G}P$	GPSv coordinates in world frame
${}^{T}P$	position expressed in TS frame
${}^{V}P_G$	GPSv coordinates expressed in vehicle O_v frame
${}^{V}_{G}R$	rotation matrix from O_g to O_v frame
${}^{V}_{T}R$	rotation matrix from O_{ts} to O_v frame
${}^{V}P_T$	position measured by TS, expressed in vehicle O_v frame
R95	radius of a circle centred at the true position, containing the position estimate with probability of 95%
r_i	measured range between B_i and B_m
t_i	timestamp of measurement r_i
TS	total station
var(x_r)	asymptotic variance of the non-linear least-squares estimator of x_r
var(y_r)	asymptotic variance of the non-linear least-squares estimator of y_r
(x_r, y_r, z_r)	estimated position of mobile beacon's antenna via trilateration
(x_i, y_i, z_i)	ith vehicle beacon antenna coordinates
(x_m, y_m, z_m)	mobile beacon antenna coordinates
ε_i	range measurement error in r_i
σ^2	variance of the range error, ε_i

Towards this goal, researchers have demonstrated that properly designed automated tractors, utility vehicles and labour aids can achieve productivity improvements that range from 20% up to 58% (Bergerman, Singh, & Hamner, 2012; Moorehead, Wellington, Gilmore, & Vallespi, 2012; Ye, He, Zhou, Zhang, & Lewis, 2013). Worker health risks, such as exposure to chemicals or ladder-related accidents can also be reduced. Research on autonomous vehicles for orchard operations has focused on problems like path planning (e.g., Bochtis et al., 2015; Linker & Blass, 2008) and navigation (e.g., Barawid, Mizushima, Ishii, & Noguchi, 2007; Zhang, Feid, & Noguchi, 1999). Less attention has been paid to autonomous operation in close proximity with humans, something that is necessary for the anticipated labour efficiency benefits to be achieved in a safe manner.

Industrial robot safety has been addressed by the International Organization for Standardization (ISO) through ISO 10218, entitled "Robots and robotic devices – Safety requirements for industrial robots," which was most recently updated in 2011 (ISO, 2011). A technical specification (ISO TS 15066), entitled "Robots and robotic devices – Safety requirements for industrial robots – Collaborative operation" addresses industrial robot operation in the proximity of humans and is still under development (ISO, 2014). This document provides information and guidance on how to achieve the safety standards described in ISO 10218. A key element in these standards is the ability to track people within a workspace and adjust robot motion according to the distance of separation between the human and robot. Although industrial and agricultural applications are not directly comparable, the ability to detect and localise nearby workers is a necessary condition for safe, "human-aware" autonomous navigation in all application areas.

Significant research has been performed in the related area of pedestrian detection and tracking in urban environments. Various active sensors such as ultrasound, radar or Lidar have been used for pedestrian detection (Gandhi & Trivedi, 2007). Extensive research on passive imaging sensors and computer vision has also been done (Dollar, Wojek, Schiele, & Perona, 2012). Bellotto and Hu (2009) used both laser scanner and vision to detect the upper and lower parts of humans. The potential utilisation of pedestrian detection techniques for improving workforce safety in agricultural environments has been discussed by Kohanbash, Bergerman, Lewis, and Moorehead (2012). Freitas, Hamner, Bergerman, and Singh (2012) use a 3D laser scanner to detect obstacles and people moving at walking speed in front of an autonomous orchard vehicle. However, the ability of cameras and laser scanners to detect humans can be affected by environmental conditions such as low illumination, haze, fog, and rain. Also, such sensors require clear line of sight (LOS), and using them to detect a worker who is located close to trees, or who is about to enter the robot's current orchard row from a neighbouring row can be very difficult due to severe LOS occlusion from tree foliage.

The goals of this paper are to present the implementation of an ultra-wideband (UWB) radio-based system for worker localisation in orchards, and to evaluate experimentally the accuracy and availability of the system at locations within the driving reach of a moving vehicle in open space and orchard environments, with and without interference from the human's body. It is envisioned that each worker will carry a mobile radio (and its small antenna), possibly attached to a belt on his/her waist. Orchard vehicles will also carry ranging radios and the worker's position will be estimated using trilateration of the antenna-to-antenna distances between the worker and the vehicle antennas. UWB transmission is a promising radio-based technology due to its power efficiency, fine spatial resolution, and robust operation in harsh environments. The Federal Communications Commission (FCC) has recently allocated a spectral mask between 3.1 and