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Improving the trajectory tracking performance of autonomous orchard vehicles using wheel slip compensation

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ABSTRACT

In this paper, the effects of wheel slip estimation and compensation of trajectory tracking for orchard applications were investigated. A slippage estimator was developed and adapted into a car-like robot model. Steering and velocity commands were generated using a model-based control approach. The whole system was implemented and tested on an autonomous orchard vehicle that has steerable front wheels and actuated rear wheels. A high accuracy positioning system was used to estimate the longitudinal and lateral slip velocities while the vehicle is moving. A laser scanning range finder was placed at the front centre of the vehicle, which was used to detect rows of trees in the orchard. Procedures were first tested in a non-flat but open space, which was covered with snow. Then it was tested on an experimental orchard where the surface was covered with heavy mud and the vehicle was expected to follow trajectories that span multiple rows in the orchard. The vehicle detected individual trees as well as rows of trees to track the centre of each row and manoeuvred from one row to the next. The experimental results showed that trajectory tracking performance of the vehicle was enhanced via integrating a slippage estimator into the system model. Furthermore, using the slippage estimation in the system model increased the accuracy, repeatability and performance of the control system.

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Nomenclature

RTK-GPS	real time kinematic – Global Positioning System
WD	wheel drive
ROS	Robot Operating System
x, y	coordinate system in the centre of the rear axle of the vehicle
X, Y	vehicle's current position
θ	vehicle orientation
ω	vehicle angular velocity
ϕ	steering angle
υ	forward velocity
L	distance between front and rear axles
V_{LF}	longitudinal slip velocity of the front wheels
V_{LR}	longitudinal slip velocity of the rear wheels
V_{SF}	lateral component of the front slip velocity
V_{SR}	lateral component of the rear slip velocity
β_F	slip angle of the front
β_R	slip angle of the rear
x_d, y_d	desired position values
θ_d	desired orientation value
υ_d	desired forward velocity of the vehicle
R	turning arc radius
y_L	distance between desired trajectory and vehicle
x_e	longitudinal error
y_e	lateral error
θ_e	orientation error
C(s)	profile of the desired trajectory
Π_{obs}	observed variables
Π_{mes}	measured values
e	observation error
k_x, k_y, k_Ω	control variables
Ω	time-varying function
λ_1, λ_2	positive time-varying functions
τ_1, τ_2	positive design parameters
δ_1, δ_2	inclination angles of the test area
υ_c	controller for the forward velocity
ϕ_c	controller for the steering angle
wo/S	without slip estimation
w/S	with slip estimation

1. Introduction

In this study, slip estimation to enhance real-time trajectory tracking performance of an autonomous field vehicle/robot was investigated. This enhancement is to improve accuracy and repeatability in trajectory tracking performance of an autonomous ground vehicle. To achieve this, a proper mathematical model is required for the vehicle that contains the necessary sensing hardware. Proper integration of sensor information into the system model is the key factor that determines the performance of a model-based controller. If performance expectation is moderate, ignoring surface effects with a flat terrain assumption yields a simplified approach. These assumptions may hold better for vehicle/robots operating indoors where surfaces are generally flat and not slippery. However, such models have restricted use in outdoors where the terrain is not necessarily smooth and slippage effect is more dramatic on the robot. In order to enhance trajectory tracking performance, by decreasing positioning errors and producing less abrupt control signals for steering, slippage information should be taken into account.

This paper presents a method for increasing the trajectory tracking performance for a vehicle used in orchards. The method proposed in this work includes the following steps: vehicle modelling, slippage estimation, stability check, and controller design for steering and velocity control. To improve tracking performance, a model-based controller is used where the estimated sideslip velocity is fed into the system model. The stability of the system is checked by using the Lyapunov approach. Experiments are conducted in both open space and in an experimental orchard-like environment using an autonomous vehicle. To observe the effects of slip estimation, these experiments are conducted with and without taking slippage estimation into account.

The paper is organised as follows: Section 2 presents the literature review followed by the statement of problem that is addressed in this study. Section 4 presents kinematic modelling and Section 5 explains the details of estimation process of sideslip angles. Section 6 introduces controller design while the desired trajectory generation is given in Section 7. Prior to the concluding remarks, experimental results including both open space and orchard studies are presented.

2. Literature review

In literature, trajectory tracking control with slip compensation is used to improve vehicles' performance under non-ideal and hence realistic conditions. Prior to the describing the proposed approach, a summary of research focussing on trajectory generation, tracking control, slippage definition and implementation for autonomous field robots is presented.

Lindgren, Hague, Smith, and Marchant (2002), modelled an autonomous guided agricultural vehicle and considered slippage. Experiments were conducted in an open space using a four-wheeled mobile robot equipped with a vision system, odometer and torque sensors. Relationships between torque and slip were investigated where a traction model was also adopted into the system model. It was shown that navigation accuracy could be improved by integrating slippage information into the system model. The method of Lindgren et al., (2002) was further improved (Lenain, Thuilot, Cariou, & Martinet, 2010) for navigation at higher speeds. Lenain, Thuilot, Cariou, and Martinet (2006) introduced an estimator for obtaining sideslip angles incorporating a high accuracy positioning system (RTK-GPS). A sideslip observer was integrated into this system model where tests were run using an autonomous farm tractor. During the experiments, the farm tractor was manually driven and the path was recorded by using the RTK-GPS at the end of which model parameters were then estimated.

Chen and Hsieh (2008), proposed a sideslip estimation methodology based on an extended Kalman filter and a bicycle model. Sideslip angle was estimated for different driving test manoeuvres in a simulation environment. Baffet,

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