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Research Paper

Reference trajectory planning under constraints and path tracking using linear time-varying model predictive control for agricultural machines

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A method for the control of autonomously and slowly moving agricultural machinery is presented. Special emphasis is on offline reference trajectory generation tailored for high-precision closed-loop tracking within agricultural fields using linear time-varying model predictive control. When optimisation is carried out, high-level logistical processing can result in edgy reference paths for field coverage. Subsequent trajectory smoothing can consider specific actuator rate constraints and field geometry. The latter step is the subject of this paper. Focussing on forward motion only, the role of non-convexly shaped field geometry, repressed area minimisation and spraying gap avoidance is analysed. Three design methods for generating smooth reference trajectories are discussed: circle-segments, generalised elementary paths, and bi-elementary paths.

1. Introduction

The agricultural sector is experiencing an increasing degree of automation in both the operation of agricultural machinery as well as farm management, Sørensen et al. (2010). This is enabled by the advent of modern computational, sensing and actuating capabilities that allow the implementation of advanced control algorithms. Within this larger context, this paper relates to efficient in-field navigation of agricultural machinery, particularly, to autonomous tractor operation (*auto-steering*).

1.1. *Literature review*

For *reference path generation*, the traditional Dubins Curves method, Dubins (1957), concatenates line segments with circular arcs of minimal admissible turning radius (maximum curvature) to generate shortest pathlength trajectories, focussing on forward motion only. This work was extended in Reeds and Shepp (1990) to also allow for backward motion, while still employing arc and straight segments. Continuous curvature (CC) path planning was then introduced by Fraichard and Scheuer (2004), now adding clothoid arcs as path segments, which in contrast to Dubins Curves, renders the overall path of not minimum length. Within an agricultural context, Backman, Oksanen, and Visala (2012b), Sabelhaus, Röben, zu Helligen, and Lammers (2013) and Backman, Piirainen, and Oksanen (2015) adopted CC path planning using clothoid arcs. The motivation is to take maximum steering rate into account to meet physical actuator constraints. While Sabelhaus et al. (2013) and

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Nomenclature

CC	Continuous curvature path planning
CoR/CoG	Centre of Rotation/Gravitation
HIOP	Headland-interval orthogonal projection
SGA	Spraying gap avoidance
U/Omega-turn	180°-turn in form of an U/Omega
(x,y,ψ)	Vehicle CoG coordinates and heading
(v,δ)	Vehicle velocity, front-axis steering angle
s	Path coordinate
R,l	Turning circle radius, wheelbase
λ	Arc fraction length

Backman et al. (2015) focussed on generating the CC paths for different turning types and allowing forward as well as backward motion, Backman et al. (2012b) implemented CC path planning in an experimental guidance system. However, they did not report quantitative closed-loop tracking errors. Thus, on the analytical level, there exists a trade-off between reference paths of shortest length and continuous curvature.

A nonlinear model predictive control (NMPC) method for a tractor system with towed implement was presented by Backman, Oksanen, and Visala (2012a). It used huge quadratic programming (HQP), Franke (1998), for the solution of its constrained nonlinear optimisation problem by the application of sequential quadratic programming (SQP). Other NMPC control strategies applied in an agricultural autonomous navigation context use the Automatic Control and Dynamic Optimization (ACADO) toolkit, Houska, Ferreau, and Diehl (2011), for the solution of their constrained nonlinear optimisation problems (Kraus et al., 2013; Kayacan, Kayacan, Ramon, & Saeys, 2015a). In Kayacan, Kayacan, Ramon, and Saeys (2015b), a linear time-invariant model predictive control (LTI-MPC) method was employed to minimise the error between a reference yaw rate and the measured yaw rate, and to find a desired steering angle. The longitudinal speed was then controlled by a proportional-integral-derivative (PID) action and an inverse kinematic controller was used for the trajectory tracking. An alternative method reported in an agricultural context is the control of chained systems, Thuilot, Cariou, Martinet, and Berducat (2002). Various closed-loop tracking accuracies have been reported based on real-world experiments. In real-world experiments, reference trajectories have frequently been generated by a human operator manually driving a specific path (e.g., Backman et al., 2012a; Lenain, Thuilot, Cariou, & Martinet, 2006). Tracking errors are usually attributed to noise or similar perturbances (e.g., wheel slip) and counter measures such as state and parameter estimators have therefore been developed.

Considering actuator rate constraints, field geometry for repressed area minimisation and spraying gap avoidance, there exists a research gap with respect to the optimal reference path generation scheme when employed in combination with a control system of interest. Conducting analysis under *nominal* conditions enables additional real-world tracking errors incurred in the field to be attributed to measurement noise and external disturbances.

1.2. *Motivation and contribution*

For reference trajectory tracking within an agricultural context, a linear time-varying model predictive control (LTV-MPC) is considered. It appears suitable in view of accurate vehicle state measurements, differential nonlinear system dynamics, the availability of efficient quadratic programming (QP) solvers, and particularly its ability to account for actuator constraints (such as maximum steering rate constraints). In this paper, the relationship between LTV-MPC and different reference trajectory generation schemes is analysed, with and without analytically continuous curvature. Therefore, the focus is entirely on nominal conditions (noise-free and full state-feedback). Concatenating a straight line with a circle-segment generates a discontinuity in curvature, but is this of practical relevance in a LTV-MPC setting. The questions posed are: How large is the discontinuity? What tracking accuracies are achievable under nominal conditions? What role do steering rate constraints, repressed area minimisation, automatic section control and spraying gap avoidance play when employing different reference trajectories? How much does interpolation of trajectories that occurs naturally within the discrete-time LTV-MPC framework affect results?

These questions are addressed below. The starting point is an edgy path plan for field coverage that was obtained from an in-field logistical optimisation step similar to that obtained by Bochtis and Vougioukas (2008), see Fig. 2. Throughout this paper the focus is to develop methods applicable to arbitrarily non-convex field contours focussing on forward motion of the agricultural machinery. Thus, the perimetric tractor lane (translated in parallel to the field contour) is assumed to be fixed. Thus, all that can be modified is the reference transition trajectories between perimetric and interior tractor lanes.

2. System modelling

2.1. *Kinematics*

Since in-field agricultural machinery operation is typically conducted at low velocity, a motion description purely based on geometric considerations is reasonable. Therefore, a

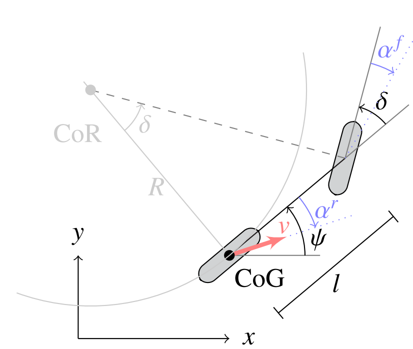

Fig. 1 – The nonlinear kinematic bicycle model (Eq. (2)). The centre of gravity (CoG) is assumed to be located at the centre of the tractor's rear axis. For model (Eq. (1)), or $\alpha^f = \alpha^r = 0$, the instantaneous centre of rotation is indicated by CoR with turning radius R.