BIOSYSTEMS ENGINEERING 139 (2015) 76–86

Available online at www.sciencedirect.com

ScienceDirect

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

Research Paper

# Smooth turning path generation for agricultural vehicles in headlands

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ARTICLE INFO

*Article history:*
Received 16 March 2015
Received in revised form
6 August 2015
Accepted 13 August 2015
Published online 30 August 2015

*Keywords:*
Path planning
Optimisation
Minimum time path
Automatic guidance
Navigation
Field traffic

Headland manoeuvring of agricultural vehicles is crucial when it comes to operational efficiency. Automatic guidance systems are usually able to parallel track but headland manoeuvring is not commonly included. Path tracking systems assume a feasible reference path can be followed but in some cases it is not trivial to generate such a path automatically. The Dubins Curves method is the traditional approach to generate the path, but this does not take into account parameters such as maximum steering rate. An algorithm is presented to generate a smooth path for headland manoeuvring where curvature and speed are continuous. Both the maximum steering rate and the maximum acceleration of the vehicle are taken into account. It is possible to define a target speed profile, either to increase or decrease the speed during the turn. The results present the functionality of the algorithm: two of the tests varied the ending pose and two others varied the parameters. The algorithm utilises numerical integration methods in one phase of the calculation, but it still generated paths in short computational time. The algorithm was found to be suitable both for use in real-time and in simulations since an average computational time of 0.36 s was achieved.



## 1. Introduction

Agricultural vehicles used in arable farming are rarely omnidirectional, i.e. the heading of the vehicle cannot be changed en route. This kind of system, which is known as non-holonomic in robotics, introduces differential constraints for the path. The structure of agricultural vehicles is driven by their functional requirements and it would be hard to add a requirement to steer all wheels independently without adding complexity in the manufacturing and design of the vehicle. The same applies for passenger cars: it would be desirable to have all-wheel steering of 180° to help in parking, but adding such a feature for current passenger car designs is not viable.

Agricultural operations take place in fields, which occur in various shapes and sizes. A typical operation in a field consists of work and transition phases, i.e. productive operations and operations such as turning. The operation can also be divided into work done in the headland and work done in the mainland; the mainland is typically the central area of the field and the headlands surround it. Depending on the agricultural operation, the order of operation on mainland and headland may vary, but the headland is the area where turns takes place; e.g. in back-and-forth driving pattern. In this article, we

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http://dx.doi.org/10.1016/j.biosystemseng.2015.08.005

**Nomenclature**

| | |
|---|---|
| LRL | Left-Right-Left (turning) |
| RLR | Right-Left-Right (turning) |
| LSL | Left-Straight-Left (turning) |
| RSR | Right-Straight-Right (turning) |
| LSR | Left-Straight-Right (turning) |
| RSL | Right-Straight-Left (turning) |
| $C_k$ | K:th elementary segment of the path |
| $S_k$ | K:th spiral segment of the path |
| $\kappa_{C_k}$ | Curvature of elementary segment $C_k$ |
| $\kappa_{S_k}(t)$ | Curvature of elementary segment $S_k$ at time $t$ |
| $t_{C_k}$ | The time instance when the element is changed from $S_{k-1}$ to $C_k$ |
| $t_{S_k}$ | The time instance when the element is changed from $C_{k-1}$ to $S_k$ |
| $t_{DC}$ | The time instance when the driving direction changes |
| $v_S$ | Driving speed in the swath |
| $v_H$ | Driving speed in the headland |
| $v_R$ | Reverse driving speed |
| $v_{C_k}(t)$ | Speed of k:th elementary segment at time $t$ |
| $v_{S_k}(t)$ | Speed of k:th spiral segment at time $t$ |
| $(x(t),y(t))$ | Position of the vehicle at time $t$ |
| $\theta(t)$ | Heading of the vehicle at time $t$ |
| $\theta_{S_k}(t)$ | Direction of the path tangent at time $t$ |
| $\Omega(t)$ | $(\Omega_x(t), \Omega_y(t))$ The centre position of the momentary turning circle at time $t$ |
| $\Omega_k$ | Centre position of the turning circle of the k:th elementary segment |
| $\Omega_{S_k}(t)$ | Centre position of the momentary turning circle of the k:th spiral segment at time $t$ |

define the paths with continuous work as swaths and the paths between as swath-to-swath turnings, or simply turnings.

Swath paths for automatic guidance can be generated by using coverage path planning algorithms for open field operations, e.g. by using parallel track generation with traversal sequences to optimise the field traffic (Bochtis & Vougioukas, 2008). Swaths may be either parallel or set according to some suitable pattern, the challenge is to create the turning paths that connect these sequential swaths. In some cases, the swaths are predetermined by the structure of the field, such as in orchards. Bochtis et al. (2015) used Dubins' Curves (Dubins, 1957), to calculate the lengths of the headland turns while optimising the field traffic in orchards.

The automatic generation of swath-to-swath turns is required by both the real-time guidance and offline coverage path planning systems. In both cases it is not only important to have feasible and near-optimal solutions, but the computational efficiency of the automatic generation algorithm has to be good. In real-time systems, the on-board processor may be the limiting factor and in offline coverage system the number of iterations may be large. A feasible solution for the automatic generation of turning paths means that the constraints of the solution are met, not only the differential constraints of the path, but also the dynamic properties of the actuator are taken into account. In practise, the actuator dynamic properties are defined as the maximum acceleration/deceleration of the vehicle and the maximum steering rate. A feasible path is necessary for advanced path tracking algorithms that may not work unless the reference path is feasible, especially if the path tracking algorithm utilises nonlinear programming techniques. As well as feasibility, it is also critical that the algorithm is able to generate a solution in all scenarios otherwise real-time systems may fail.

The commonly known method to generate the shortest path between two arbitrary positions is to use Dubins Curves (Dubins, 1957). The Dubins Curves consist of curves with minimum turning radius and line segments connected together. The problem is that at the junction point of the path, the vehicle would have to either stop or turn wheels infinitely fast, which is not feasible in practical applications. Another approach is to use a mathematical optimisation methods to calculate the shortest path between two positions. Constraints can be met, but the computational cost is high.

To prevent discontinuities in the Dubins or Reeds-Shepp Curves (Reeds & Shepp, 1990), different solutions have been proposed. Parlangeli and Idiveri (2010) proposed a method for calculating a smooth path with bounded curvature and curvature derivative. However, the method is applicable only when there is a straight line segment between two arcs. Fraichard and Scheuer (2004) proposed a method to extend Reeds and Shepp turning curves to paths with continuous and upper-bounded curvatures and an upper-bounded curvature derivative. However, in certain cases, the method does not produce paths that have optimal length. In these cases, the curvature derivative is allowed to be less than maximum. The method is only designed to connect configurations with null curvature.

Sabelhaus, Röben, Meyer zu Helligen, and Schulze Lammers (2013) proposed using a method based on the clothoid construction elements, which enables smooth connection from zero curvature to maximal curvature and using it together with Dubins Curves. Sabelhaus et al. (2013) defined seven different manoeuvres as useful out of the full set. The approach is limited to fixed speeds during the turn.

There are also various proposals based on numerical optimisation (e.g. Fernandes, Gurvits, & Li, 1991 and Oksanen, 2007). The problem with numerical optimisation is the computational complexity. The algorithms require plenty of computational power and there is no guarantee that a solution will be achieved within a given time window.

In this article, a complete approach to provide automatic turning path generation with variable speed profile and actuator dynamics for a non-holonomic vehicle, from the initial state (position, heading, curvature and speed) to the final state is presented. The variable speed profile during the turn may be used either by increasing the speed during the turning path compared with operational speed to make it faster, or by lowering speed in the turn to improve stability or allowing an on-board operator to monitor environment better during the turn.

## 2. Methods

Dubins (1957) has shown that, if a vehicle has limited curvature and only forward motion is allowed, the minimum path between two arbitrary positions is found in the set of six