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Research Paper

Partial field coverage based on two path planning patterns

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This paper presents a path planning method for partial field coverage. Therefore, a specific path planning pattern is proposed. The notion is that lighter machinery with smaller storage tanks can alleviate soil compaction because of a reduced weight, but does not enable full field coverage in a single run because of the smaller storage capacity. This is relevant for spraying applications and related in-field work. Consequently, multiple returns to a mobile or stationary depot located outside of the field are required for storage tank refilling. Therefore, a suitable path planning method is suggested that accounts for the limited turning radii of agricultural vehicles, satisfies compacted area minimisation constraints, and aims at overall path length minimisation. The benefits of the proposed method are illustrated by means of a comparison to a planning method based on the more common AB pattern. It is illustrated how the proposed path planning pattern can also be employed efficiently for single-run field coverage.

1. Introduction

According to Ahumada and Villalobos (2009) and Bochtis (2010), the agri-food supply chain can be decomposed into four main functional areas: production, harvesting, storage and distribution. For improved supply chain efficiency, logistical optimisation and route planning play an important role in all of the four functional areas. Regarding production, for example, by means of minimisation of the non-working distance travelled by machines operating in the headland field according to Bochtis and Vougioukas (2008), optimal route planning based on B-patterns according to Bochtis, Sørensen, Busato, and Berruto (2013), or route planning for the coordination of fleets of autonomous vehicles as discussed in Conesa-Muñoz, Bengochea-Guevara, Andujar, and Ribeiro (2016a) and Seyyedhasani and Dvorak (2017). See also Day (2011) for an overview of means for efficiency improvements, Bochtis (2013) for the importance of satellite-based navigation systems in modern agriculture, and Sorensen & Bochtis (2010) and Jensen et al. (2012) for a distinction between in-field, inter-field, inter-sector and inter-regional logistics. The path planning method for partial field coverage presented in this paper relates to the first functional area of the agri-food supply chain.

The last decades have witnessed a trend towards the employment of larger and more powerful machines in agriculture. This trend is expected to further continue in the near future, see Kutzbach (2000) and Dain-Owens, Kibblewhite, Hann, and Godwin (2013). Among the main benefits are higher work rates. The drawbacks include increased soil compaction

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Nomenclature

Symbols

$D^{(\rho)}$	Total in-field path length for $\rho \geq 1$ field runs (m)
ΔD	Path length difference (m)
$e_{i,j}$	Edge connecting nodes i and j (m)
$f(t)$	Storage tank fill-level (%)
$\gamma(t)$	Vehicle state (resume, coverage, return)
H_0	Nominal lane path length in a rectangular field (m)
N	Number of interior lanes (–)
q_l, p	Auxiliary variables in the example of Section 4.1 (–)
ρ	Number of field runs required for field coverage (–)
R	Vehicle turning radius (m)
W_0	Nominal machine operating width (m)
Z	Position $Z = (\xi, \eta)$ (m)
(x, y)	Position in the global coordinate system (m)
(ξ, η)	Position in the normalised coordinate system (m)
Z_0	Start position $Z_0 = (\xi_0, \eta_0)$ (m)
$\mathscr{Z}_0^{(l)}$	Two sets of start positions with $l = 1, 2$ (m)
Z_i	Position of node i (m)
$Z(t)$	Position of agricultural vehicle at time t (m)
$Z(\tau^{\text{last}})$	Position for resuming field coverage (m)

Abbreviations

ABp	Path Planning Method 1 (AB pattern)
CIRC	Path Planning Method 2 (circular pattern)
CIRC*	Path Planning Method 3 (circular pattern)

due to machinery weights, see Raper (2005), Hamza & Anderson (2005), Antille et al. (2016), Bochtis et al. (2010). See also Antille, Ansorge, Dresser, and Godwin (2013) for the influence of tyre sizes on soil compaction. Concurrently to this ongoing trend, there are alternative considerations about the replacement of heavy machinery by teams of smaller and lighter autonomous robots to mitigate soil compaction, see Blackmore, Fountas, Gemtos, and Griepentrog (2008), Bochtis and Sørensen (2010), Bochtis, Sørensen, and Green (2012), Bochtis (2013), Gonzalez-de Santos et al. (2016) and Seyyedhasani and Dvorak (2017). See also Vougioukas (2012) for a method for motion coordination of teams of autonomous agricultural vehicles.

This paper is motivated by the concept of smaller in-field operating machines collaborating with out-field support units (mobile depots). Therefore, a pattern-based path planning method for partial field coverage is presented, which is characterised by i) minimisation of travelled non-working path length, and ii) compliance with compacted area minimisation constraints. The latter implies driving along unique and established transitions between headland path and interior lanes, thereby avoiding the creation of any additional tyre traces that result from vehicle traffic passing over crops and compacting soil. Under the assumption of specific field shapes two different path planning patterns are compared.

In contrast to route planning methods such as in Conesa-Muñoz, Pajares, and Ribeiro (2016b) for the in-field operation of a fleet of vehicles, the presented method focuses on the in-field operation of a single vehicle that is repeatedly returning to the field entrance for refilling, similarly to Jensen et al. (2015). This is primarily motivated by the targeted crops (wheat, rapeseed and barley) and the costs of corresponding agricultural vehicles. A support unit, acting as a mobile depot, is assumed to be waiting at the field entrance for refilling. Two comments are made. First, unlike during harvest, mobile units for refilling of spraying tanks cannot come to any arbitrary position along the headland. Second, a single field entrance is in line with the objective of compacted area minimisation. For aforementioned targeted crops, any new field entrance would result in a new compacted area for the connection of in-field headland path and out-field road network, see Fig. 1.

This paper is organised as follows. The problem is formulated in Section 2. The main contribution is given in Section 3. Examples and a discussion are presented in Sections 4 and 5, before concluding with Section 6.

2. Problem formulation and notation

2.1. Problem formulation

This paper addresses pattern-based path planning for partial field coverage. The fundamental objective is non-working path length minimisation. Therefore, the following is additionally addressed.

First, path planning must account for *compacted area minimisation constraints*. These constraints impose unique transitions between headland and interior lanes and account for limited turning radii. For illustration see Fig. 2. Any agricultural vehicle that is travelling along lanes and the headland path must respect tractor traces established upon first field coverage. Thus, transitions P-Q and P-D are admissible. In contrast, transition P-C is not admissible. Such a transition would deviate from established tyre traces when accounting for the limited turning radius of the vehicle, and would therefore repress and destroy precious crop. See also Graf Plessen and Bemporad (2016) for general shortest path in-field navigation accounting for these constraints.

Second, path planning must ideally minimise non-working path length for *both* single-run and partial field coverage.

Third, path planning must optimally account for the following tasks during online operation: i) path following according to a field coverage plan, ii) navigation from a position along the path network to the field entrance for refilling of storage tanks, and iii) navigation from the field entrance after refilling back to the position along the field coverage path for the resumption of work.

2.2. Assumptions on field shapes and notation

The focus of this paper is on field shapes that permit optimal path planning based on patterns, see Fig. 3. As will be shown, for these field shapes the preferred pattern-based path planning method can yield minimal path length solutions for both full and partial field coverage. Relevant components for planning include a headland path and multiple interior lanes, see Fig. 4. In combination, they enable field coverage. The