PERFORMANCE OF AUTONOMOUS NAVIGATION IN AN AGRICULTURAL TRACTOR USING PURE PURSUIT CONTROL AND DUBINS PATH PLANNING

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Abstract.
Accurate path tracking is a key requirement for autonomous agricultural vehicles operating in precision agriculture. However, the performance of autonomous navigation systems is strongly influenced by the interaction between path-planning constraints, vehicle kinematics, and controller tuning parameters. Computational simulations provide an effective framework for evaluating these interactions and identifying operating conditions that maximize navigation performance. This study evaluated the path-tracking performance of an autonomous agricultural tractor employing Dubins path planning and Pure Pursuit control. Simulations were conducted using a kinematic model representative of a John Deere 5705 4×2 MFWD tractor with Ackermann steering kinematics. The reference path consisted of three parallel straight-line segments, each 13.7 m long and spaced 3.2 m apart, connected by Dubins-generated headland turning maneuvers. The planned path was discretized into waypoints spaced at 0.5 m intervals. A total of 360 parameter combinations were evaluated, considering six forward-speed levels (2.3–10.6 km h^{-1}), five turning-radius levels (3–7 m), and twelve look-ahead distance levels (0.6–6.1 m). Only simulations exhibiting stable path-tracking behavior were considered valid, resulting in 236 successful cases. Performance was quantified using the root mean square error (RMSE) of the cross-track error (XTE) between the vehicle trajectory and the reference path. The results demonstrated that, for each combination of forward speed and turning radius, an optimal look-ahead distance exists that minimizes tracking error. The relationship between look-ahead distance and XTE was strongly nonlinear. Larger turning radii generally reduced XTE by requiring smoother steering actions, whereas lower forward speeds improved tracking accuracy by reducing control demand. Increasing the look-ahead distance enhanced closed-loop stability but could increase tracking error due to slower convergence to the reference path. Conversely,

excessively short look-ahead distances produced aggressive steering responses and increased the likelihood of oscillatory behavior and instability. Overall, the findings indicate that navigation performance depends on the combined design of the path-planning and path-tracking subsystems. For each operating condition, an appropriate look-ahead distance must be selected to balance stability and tracking accuracy. These results support the development of adaptive navigation strategies for autonomous agricultural vehicles operating under varying field conditions.

Keywords.
Autonomous agricultural vehicles; Precision agriculture; Path planning; Path tracking control; Pure Pursuit; Dubins paths; Cross-track error; Agricultural robotics.

Introduction

Precision and digital agriculture increasingly rely on operations with high spatial repeatability, where autonomous navigation systems can reduce skips, overlaps, and operational inefficiencies. In autonomous ground vehicles, navigation performance depends on the compatibility between the reference path, vehicle steering constraints, and path-tracking controller parameters.

In field operations involving parallel crop rows, transitions between adjacent passes require maneuvers that satisfy the vehicle's minimum turning radius and the available headland space. Path plans that neglect these constraints may generate infeasible steering commands, resulting in increased cross-track error (XTE) and potentially unstable vehicle behavior.

The Dubins algorithm is a widely adopted path-planning approach for nonholonomic vehicles with bounded curvature. It generates feasible paths composed of straight-line segments and circular arcs, making it particularly suitable for agricultural vehicles that predominantly operate in forward motion (Dubins, 1957; LaValle, 2006). The resulting path can be discretized into waypoints and tracked using geometric controllers such as Pure Pursuit.

The Pure Pursuit algorithm computes the steering curvature required to drive the vehicle toward a target point located ahead of its current position along the reference path. The distance to this target point, known as the look-ahead distance, is the primary tuning parameter of the controller and has a significant influence on tracking performance and closed-loop stability (Coulter, 1992; Paden et al., 2016).

Because vehicle forward speed and maneuver curvature also affect steering demand and path-tracking difficulty, the look-ahead distance should not be treated as a fixed parameter for all operating conditions. Therefore, this study evaluates, through computational simulations, the combined effects of forward speed, turning radius, and look-ahead distance on cross-track error and path-tracking stability in an autonomous agricultural tractor employing Dubins path planning and Pure Pursuit control.

Materials and Methods

The study was conducted in a computational simulation environment using the Python programming language. The simulated vehicle represented an agricultural tractor with Ackermann steering kinematics and geometric characteristics compatible with a John Deere 5705 4×2 MFWD tractor, considering front-wheel steering and propulsion applied only to the rear wheels (mechanical front-wheel drive disengaged).

A simplified kinematic bicycle model was adopted, which is appropriate for low-speed operation where dynamic effects are generally secondary to the vehicle's geometric behavior (Paden et al., 2016). The model equations are presented in Equation (1).

$$\mathbf{x}(t) = \begin{bmatrix} x(t) \\ y(t) \\ \theta(t) \end{bmatrix}, \quad \dot{\mathbf{x}}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} v(t)\cos\theta\,(t) \\ v(t)\sin\theta\,(t) \\ \dfrac{v(t)}{L}\tan\delta\,(t) \end{bmatrix} \tag{1}$$

where x and y represent the position of the vehicle control point in the Cartesian plane, θ is the vehicle heading angle, v is the forward velocity, L is the wheelbase, and δ is the equivalent steering angle. These equations were used to update the vehicle state at each simulation step.

The reference path represented a typical parallel-pass field operation and consisted of three straight-line segments, each 13.7 m long and spaced 3.2 m apart. The transitions between adjacent passes were generated using the Dubins path-planning algorithm with a constant turning radius defined for each simulation. After path generation, the reference path was discretized into waypoints spaced at 0.5 m intervals (Fig. 1).

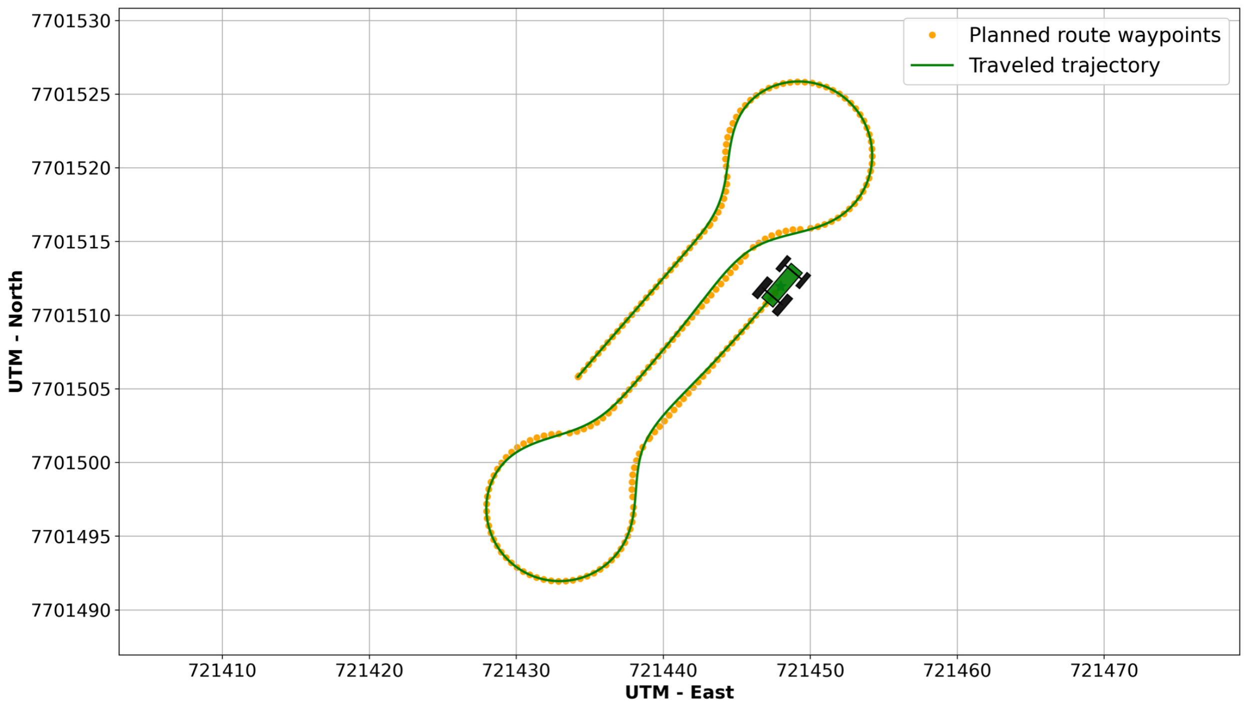

Fig. 1. Example of a Dubins-generated reference path and the corresponding simulated vehicle trajectory using Pure Pursuit control.

A total of 360 parameter combinations were evaluated, including six forward-speed levels (2.3–10.6 km h⁻¹), five turning-radius levels (3–7 m), and twelve look-ahead distance levels (0.6–6.1 m). Only simulations in which the controller successfully completed the entire path without persistent oscillations or loss of convergence were considered valid.

Navigation performance was evaluated using the cross-track error (XTE), defined as the minimum Euclidean distance between the vehicle position and the reference path. The root mean square error (RMSE) of the XTE was adopted as the performance metric, since it penalizes larger deviations and facilitates comparisons among parameter combinations (Gan-Mor et al., 2007; Zhang et al., 2021).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} e_i^2 \, d_i}{\sum_{i=1}^{N} d_i}} \tag{2}$$

where e_i is the cross-track error at sampled point i along the vehicle trajectory, d_i is the distance between consecutive sampled points of the traveled trajectory, and N is the total number of sampled points. The distance-based weighting ensures that the RMSE is independent of the local sampling density, since regions traversed at lower speeds contain more sampled points per unit of distance. Lower RMSE values indicate greater path-tracking accuracy.

Results and Discussion

Controller Stability

Among the 360 parameter combinations evaluated, 236 (65.6%) exhibited stable path-tracking behavior and were considered valid. The discarded cases were primarily associated with excessively aggressive steering responses, oscillatory behavior, or convergence failures in regions with higher path curvature.

These results indicate that navigation stability depends on the combined tuning of both the path-planning strategy and the path-tracking controller. In practical agricultural applications, inadequate parameter selection may increase cross-track error, generate overlap between adjacent passes, and elevate the risk of excessive proximity to crops, field boundaries, or obstacles.

Effect of Look-Ahead Distance

For each combination of forward speed and turning radius, an optimal look-ahead distance was observed that minimized cross-track error, revealing a clear nonlinear relationship (Fig. 2). Increasing the look-ahead distance reduced controller aggressiveness up to a certain threshold. Beyond this point, however, the controller response became excessively smooth, delaying convergence toward the reference path.

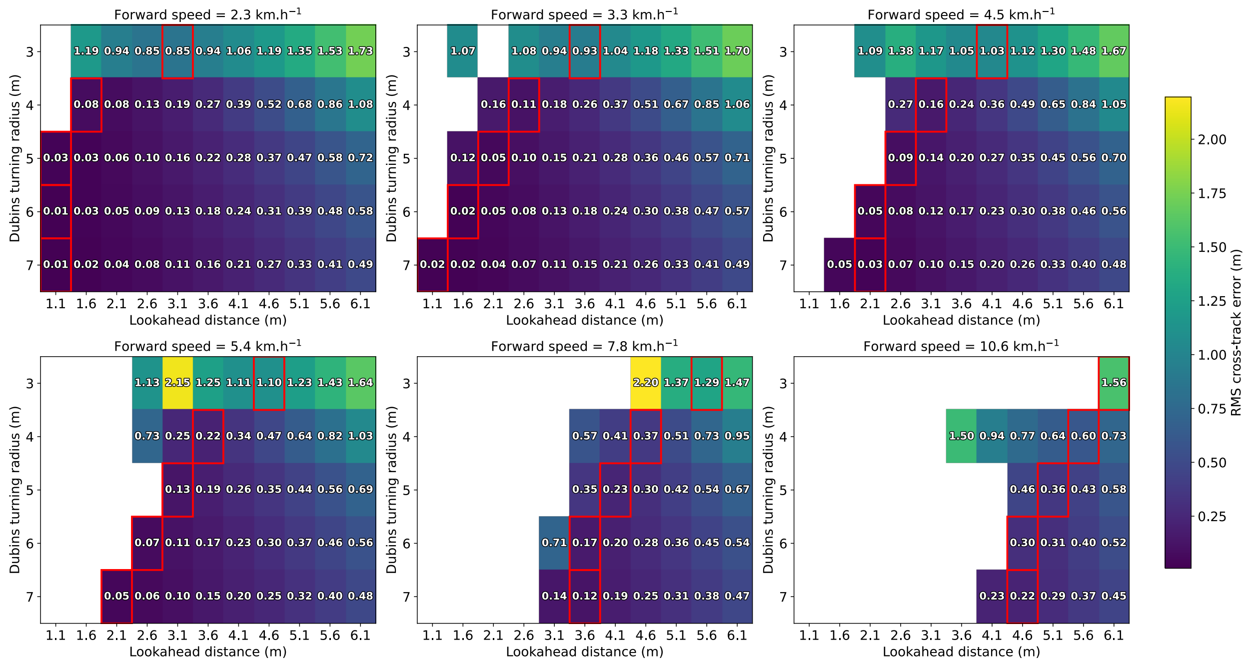

Fig. 2. RMSE heatmaps for combinations of forward speed, turning radius, and look-ahead distance. White regions indicate unstable or invalid operating conditions. Red rectangles highlight the parameter combinations that resulted in the lowest RMSE values for each forward speed.

Short look-ahead distances generated rapid steering corrections, which could reduce tracking error along relatively simple path segments. However, they also increased the likelihood of oscillations and instability during turning maneuvers. Conversely, larger look-ahead distances improved stability but tended to increase cross-track error in curved sections, where the target point became less representative of local path geometry.

Effect of Turning Radius

Larger turning radii reduced cross-track error because they required lower instantaneous path curvature and smoother steering commands. This condition favored Pure Pursuit performance, as the look-ahead point remained better aligned with the future direction of travel.

Although larger turning radii improved tracking accuracy and stability, they also required greater headland area for maneuver execution. Smaller turning radii produced more compact maneuvers but increased steering demand and the likelihood of instability, particularly at higher operating speeds or when combined with inadequate look-ahead distances.

Effect of Forward Speed

Lower forward speeds reduced cross-track error and expanded the range of stable parameter combinations. Under these conditions, the vehicle traveled a shorter distance between control updates, requiring less abrupt steering corrections.

As forward speed increased, the controller was required to compensate for deviations within shorter time intervals, resulting in larger cross-track errors, especially in curved path segments. Therefore, operating speed should be selected by balancing navigation accuracy and field productivity.

Summary of Observed Effects

The existence of an optimal look-ahead distance for each operating condition indicates that parameter selection for autonomous agricultural vehicles should account for vehicle speed, path curvature, and the available maneuvering space. Table 1 summarizes the effects of the main parameters evaluated and their implications for the performance of autonomous navigation systems in agricultural tractors.

Table 1. Qualitative synthesis of the effects of parameters on autonomous navigation system performance.

Parameter	Observed trend	Benefit	Operational limitation
Short lookahead	More aggressive response	May reduce error in simple segments	Increases risk of oscillation and instability
Long look-ahead	Smoother response	Increases controller stability	May increase XTE in curves and delay convergence
Smaller turning radius	Higher steering demand	Requires less headland area for maneuvers	Increases lateral error and makes maneuvers more aggressive
Larger turning radius	Lower steering demand	Reduces lateral error and smooths maneuvers	Requires larger headland area
Lower speed	More gradual corrections	Improves precision and stability	Reduces operational capacity
Higher speed	Less time available for corrective steering	Increases field throughput	May increase error and restrict stable parameter combinations

Conclusions

The results demonstrate that efficient autonomous navigation of agricultural tractors requires the integration of curvature-constrained path planning and appropriate path-tracking controller tuning. For a given combination of forward speed and turning radius, an optimal look-ahead distance exists that minimizes cross-track error while maintaining stable closed-loop behavior.

Larger turning radii generally improved tracking accuracy and stability by reducing steering demand, although they require greater headland space for maneuver execution. Lower forward speeds also reduced cross-track error and expanded the range of stable operating conditions, albeit at the expense of field productivity.

These findings indicate that controller parameters should be selected according to the operational scenario rather than using a single fixed configuration. Future work should investigate adaptive look-ahead strategies capable of adjusting controller parameters in real time according to vehicle speed, path curvature, and environmental conditions, with the objective of improving tracking accuracy and robustness during agricultural operations.

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