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Path planning of headland turn manoeuvres

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Satellite-based navigation systems offer the possibility to steer agricultural machinery on the field automatically within a range of centimeters. A reference line is recorded and – based on the position – shifted, so that the entire field can be covered with parallel tracks. However, automatic turn manoeuvres from path to path are not yet part of the standard scope of steering systems.

This article presents a method to generate feasible headland turn manoeuvres. Speed, minimum turning radius and the systemic steering speed are used as vehicle-specific parameters to plan feasible trajectories. An adaptation of the continuous-curvature path planning – known from mobile robotics – is applied. It was verified that the generated turn routines could be driven by real machines with steering systems. A precise connection between turn manoeuvre and track was ensured.

Keywords
Path planning, GPS steering system, headland turn manoeuvre

Automatic steering systems are increasingly used in modern agriculture to process fields efficiently. Tractors and harvesters can use real-time kinematic to navigate on the field in the range of a few centimeters. For precise vehicle guidance while turning and other steering-intense manoeuvres, the path planning must be adapted to the machine kinematics and dynamics. Below, an adapted method of trajectory planning via continuous-curvature paths is explained and finally verified.

Material and methods

To enable steering systems for automatic turning, a realistic trajectory for the machine must be estimated. These routes obey three main criteria that are presented in Figure 1 and must be known for path generation.

- The minimum turning radius $\frac{1}{\kappa}$ can be calculated automatically by the steering system with known maximum steering angle and wheel base.
- Further, the maximum lateral acceleration $a_{y,\,max}$ is shown in Figure 1 (centre). With this value, the maximum steering angle $\frac{d\delta}{dt}$ is limited by the speed, so that the vehicle's driving behaviour remains stable and neither over- nor understeers.
- The third limiting variable is the steering speed, which describes the time the actuator system changes of maximum left to maximum right steering lock.

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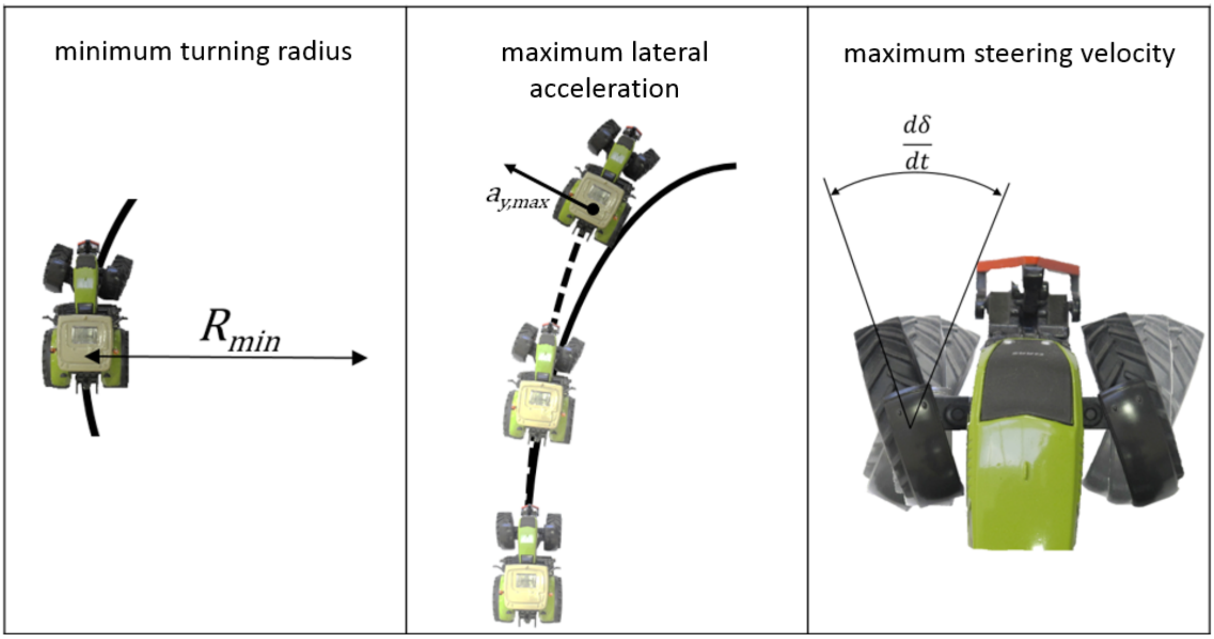

Figure 1: Requirements for a planned trajectory: minimum turning radius, maximum lateral acceleration and maximum steering speed

Some articles have already presented methods to generate turning paths. Oksanen (2007) generated turning paths with segments of Bézier splines to minimize the length of the turning path. The turn manoeuvre length shall be minimized with cost functions. The complex tractor-trailer combination is defined as a common field vehicle and used for problem modelling. It is modelled as a dynamic system with 6 states and 2 inputs, restricted in 2D motion. Scheuren (2014) shows a method to generate headland paths for the kinematics of a tractor-like vehicle using grid-based motion primitives. In order to achieve the most accurate driving connection to a subsequent track, a very fine-meshed grid with potential trajectory points is investigated. Vougioukas et al. (2006) calculate the trajectories numerically using a two-part motion planner and a predefined cost function.

One opportunity to generate feasible trajectories is given by the method of continuous-curvature path planning (CC-path planning). In 1997, it was presented by Scheuer and Fraichard (1997) to generate feasible paths between start and end positions. The main advantage is that continuous curvature transitions are given (Figure 2). In both representations a start and end point with start and end orientation are connected with a trajectory. The composition of minimum turning circles and straight lines can be seen in the left illustrated track – also known as Dubins curve (Dubins 1957). The curvature course is shown among the Dubins curve. A discontinuity of curvature occurs in transition from circle to straight segment. This progress means that the steering wheel position changes abruptly from the maximum right turn to straight. Thus, the trajectory can not be driven at a constant speed, the vehicle has to be stopped at the black circled transition point. This clear curvature progress can be avoided by inserting spiral pieces – called clothoids. The clothoid is described by maximum curvature change of $\sigma = \dot{\kappa} = +\sigma_{max}$. The curvature change is the first derivative of the curvature and thus indicates whether a constant curvature is given. With this introductory clothoid, the curvature increases from $\kappa = 0$ to $\kappa = \kappa_{max}$. The curvature describes the arcuate deviation of a straight line and is the reciprocal of the radius.

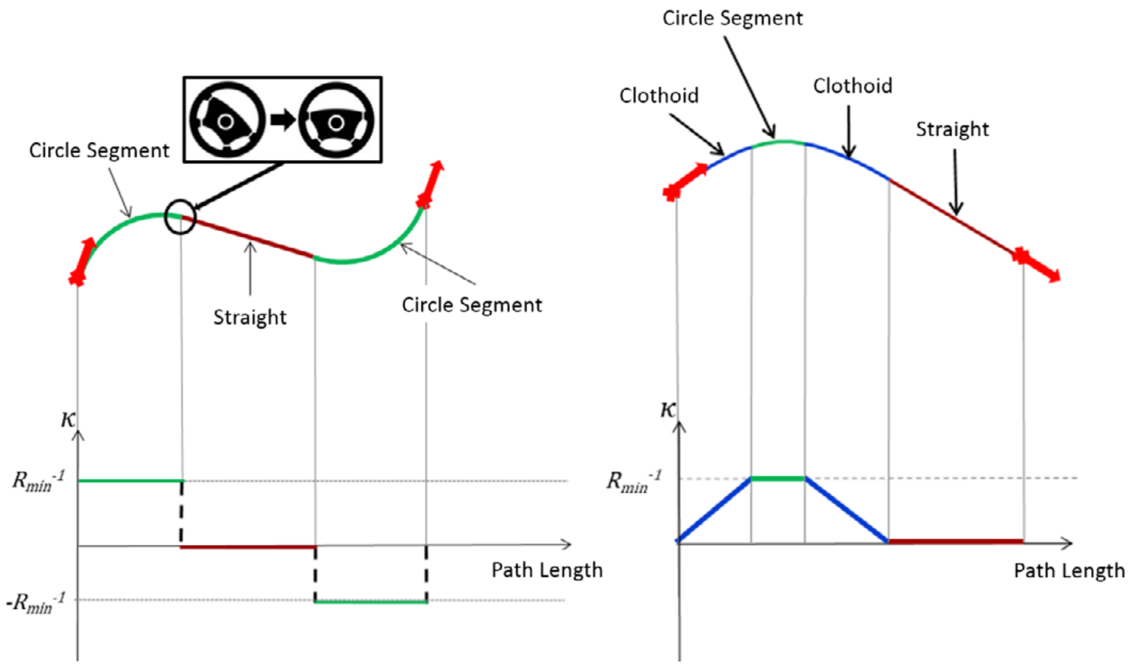

Figure 2: Representation of the curvature profiles of Dubins curves (Dubins 1957) (left) and CC-Paths (Scheurer and Fraichard 1997) (right)

The characteristic of a clothoid is the linear change of curvature with which the curvature varies in proportion to the clothoid length. Kimia et al. (2003) describe the clothoid trajectory points using the Fresnel integrals C_f and S_f. The circle centre Ω with its coordinates Ω_x and Ω_y for the CC-turn can be determined by the Fresnel integrals of the introductory clothoid. Scheuer and Fraichard (2004) have described the formulas with the parameter p $[0, p_{max} = \frac{\kappa_{max}^2}{\pi\sigma_{max}}]$ and the basic clothoid parameters x, y. θ describes the angle of clothoid end points to CC-circle centre.

$$\Omega_x = x_{Klothoide}\left(\frac{\kappa_{max}^2}{\pi\sigma_{max}}\right) - \kappa_{max}^{-1} \cdot \sin(\theta) \quad \text{(Eq. 1)}$$

$$\Omega_y = y_{Klothoide}\left(\frac{\kappa_{max}^2}{\pi\sigma_{max}}\right) + \kappa_{max}^{-1} \cdot \cos(\theta) \quad \text{(Eq. 2)}$$

In the following, the general case of a CC-turn is listed. The radius R_{big} is defined as the distance between circle centre and starting point. Equation 3 illustrates the relationship.

$$R_{big} = \sqrt{(\Omega_x - x_{Klothoide}(0)^2) + (\Omega_y - y_{Klothoide}(0)^2)} \quad \text{(Eq. 3)}$$

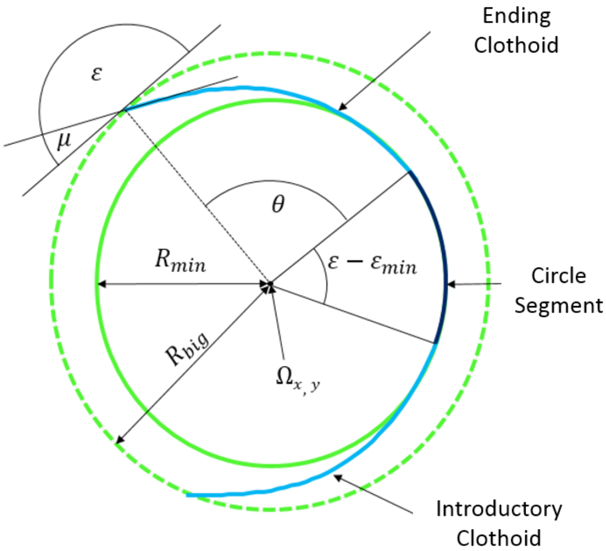

Figure 3: General case of a CC turn with circle centre Ω

Figure 3 shows the construction elements of a CC-circle with angle μ and the associated counter-angle ε. The angle μ is between the tangent at the CC-circle entry/exit point and the clothoid start/end orientation. They can be calculated as follows.

$$\mu = \pi - \varepsilon = \mathrm{atan}\left(\frac{\Omega_x - y_{Klothoide}(0)}{\Omega_y - y_{Klothoide}(0)}\right) \quad \text{(Eq. 4)}$$

The angle ε also indicates the difference between start and end orientation. The minimum angle difference is defined as $\varepsilon_{min} = \kappa_{max}^2 \cdot \sigma_{max}^{-1}$. In case of small angle differences ($|\varepsilon| \leq \varepsilon_{min}$), a complete surrounding circle needs to be planned according to FRAICHARD and SCHEUER (2004). To avoid this path, they have presented an elementary path. This elementary path has a curvature change $\sigma \leq \sigma_{max}$. The required change in curvature can be specified with:

$$\sigma = \frac{\pi(\cos(\frac{\varepsilon}{2})C_f(\sqrt{\frac{\varepsilon}{\pi}}) + \sin\left(\frac{\varepsilon}{2}\right)S_f(\sqrt{\frac{\varepsilon}{\pi}}))^2}{{R_{big}}^2 sin^2(\frac{\varepsilon}{2} + \mu)} \quad \text{(Eq. 5)}$$

Thus, two symmetrical clothoid segments can be computed and merged (Figure 4).

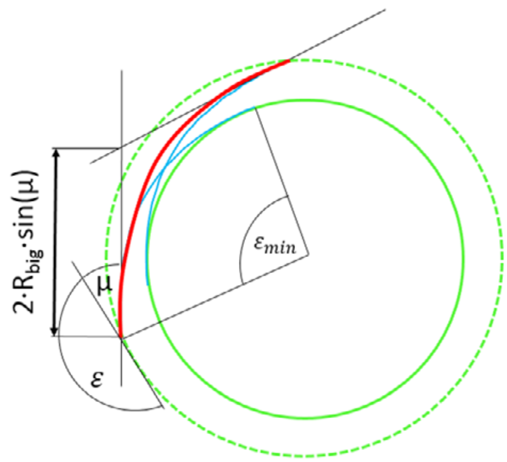

Figure 4: CC turn for angle differences 0 < ε < ε_{min}

In order to transfer this idea of CC path planning to path planning of agricultural machinery, the following formula connects these two areas.

$$l_{Klothoide} = \frac{t_{Lenk}}{2} \cdot v \qquad \text{(Eq. 6)}$$

The clothoid length can be described as the product of speed and half the time from maximum right to maximum left steering lock. These values are stored in today's guidance systems and can be determined while steering.

Adaption of CC-Paths for headland turn manoeuvres

Using CC-circles, feasible paths for agricultural machinery can be generated which are limited by a minimum turning radius and a maximum curvature change. The indicated turning manoeuvres are acceptable for the track distances *d* that are specified by value ranges in the given formulas of Figure 5.

First, the Omega turn is presented whose trajectory resembles the Greek letter. This manoeuvre is usual for turning with small working widths into an adjacent, parallel track. It can be described as a left-right-left or right-left-right steering combination. This CC path is shown in Figure 5 (left) and can be constructed by three CC circles. If the distance *d* between the start and end point is $\geq 2 \cdot R_{big} \cdot cos(\mu)$, the CC circle centre point of the upper, middle circle wouldn't be predictable. If the distance *d* between start and end point is $2 \cdot R_{big} \cdot cos(\mu) \leq d \leq 2 \cdot R_{big} \cdot cos(\mu) + 2 \cdot \sqrt{R_{big}^2 - (R_{big} \cdot \cos(\mu))^2}$, the Omega turn is not predictable. Also the U-turn is not calculable, so that a transitional solution is needed the gap turn is constructed. A right or left curve is created with three CC circles. Thereby, the middle CC circle is planned with distance x_{min} that as early as possible the introductory CC circle can be left without self-encircling and the closing CC circle can be entered.

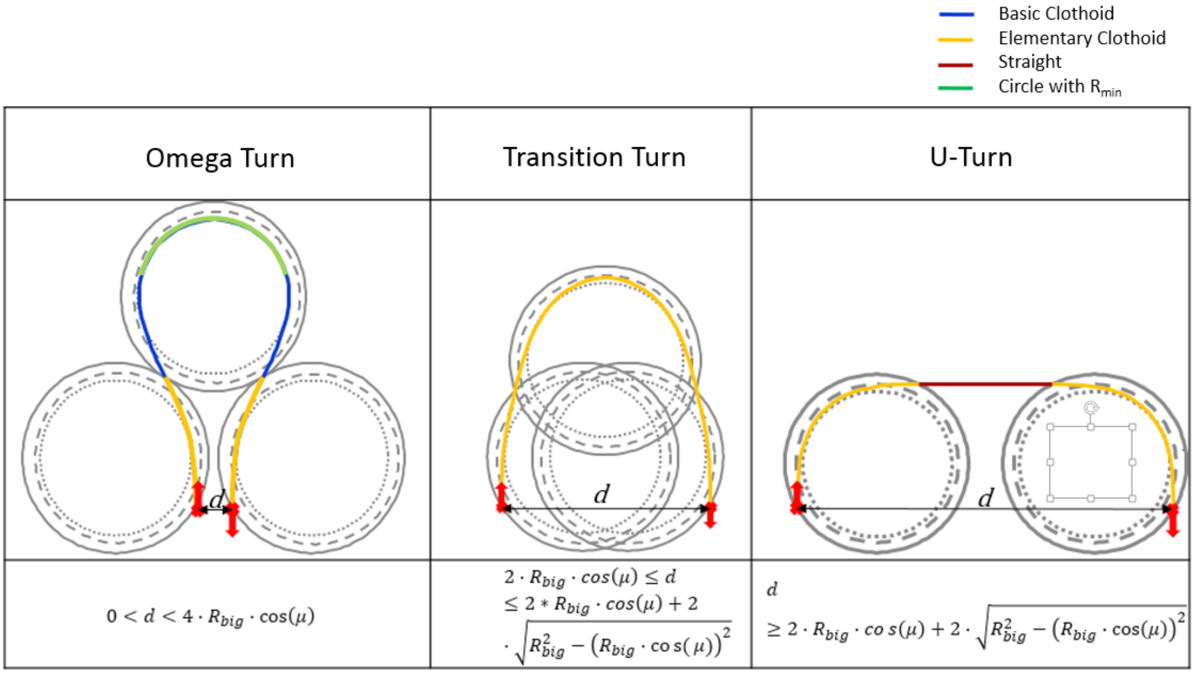

Figure 5: Adapted CC-Paths for agricultural Turn Manouevres

For all turn manoeuvres with distance $d \geq 2 \cdot R_{big} \cdot \cos(\mu) + 2 \cdot \sqrt{R_{big}^2 - (R_{big} \cdot \cos(\mu))^2}$, a U-turn is computed. This turning type consists of an introductory CC-Circle, a straight segment and a closing CC-Circle. The length of the straight segment can be described as $l_{Segment} = -\Omega_{x,start} - R_{big} \cdot \sin(\mu) + \Omega_{x,end} - R_{big} \cdot \sin(\mu)$

With the three shown manouevres, all configurations of turn distances can be computed. However, the shortest path length won't be found in each configuration. More, predictable manoeuvres are not shown in this article. Sabelhaus et al. (2013) show further manoeuvres by CC-path planning in agricultural scenarios. For example, the so-called fishtail turn with two direction changes can be planned. Also minimising the headland was in the focus of turn manoeuvre planning.

Results

As soon as the vehicle enters the headland area, a turn manoeuvre shall be planned and driven autonomously. It must be examined whether the generated paths obey the machine restrictions with regard to the kinematics. Because of the variety of turn manoeuvres, the results of an Omega turn are shown exemplary. The turning into an adjacent track is investigated. The important parameters, which describe a trajectory with regard to drivability, are curvature and curvature change (Fraichard und Scheuer 2004). Without vehicle modell and simulation, these parameters can be derived by the planned trajectory. A cubic spline – a function which is concatenated by piecewise polynomial functions with nth degree – and its curvature calculation is used for trajectory analysis. The formula is shown in Equation 7 with its component functions x and y. The curvature change is derived as time-based curvature.

$$\kappa(t) = \frac{\dot{x}(t)\ddot{y}(t) - \ddot{x}(t)\dot{y}(t)}{(\dot{x}(t)^2 + \dot{y}(t)^2)^{\frac{3}{2}}} \qquad \text{Eq. 7}$$

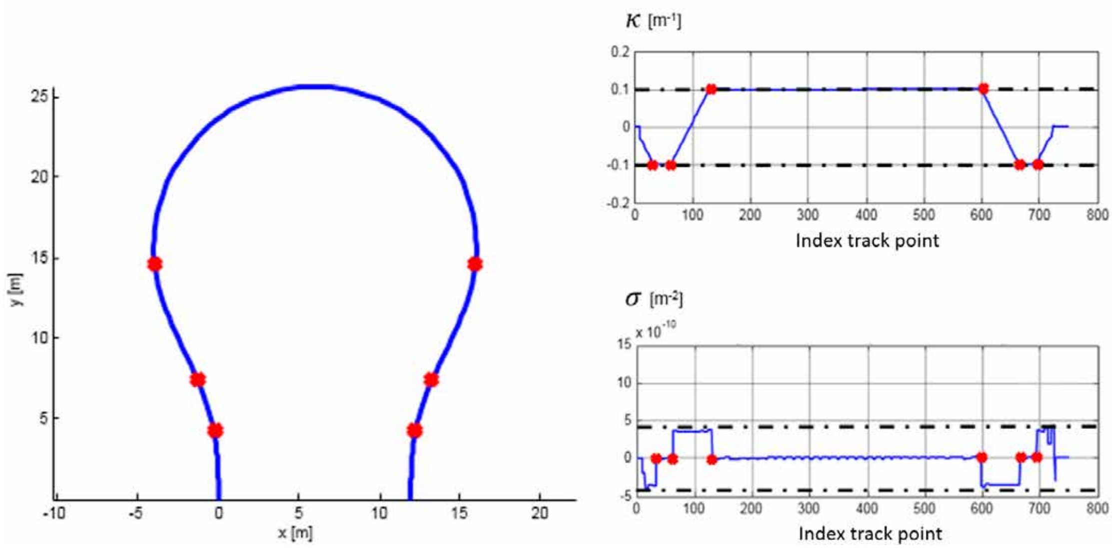

Figure 6: Courses of curvature (upper right graph) and curvature change (lower right graph) and planned trajectory (left)

Curvature and curvature change behave as expected (Figure 6, right). The graph shows a curvature course of -0,1 up to 0,1 m^{-1}, what corresponds to the reciprocal of the minimum turning radius R = 10 m. The curvature change is limited to $\sigma_{max} \approx 0{,}05\ m^{-1}\ s^{-1}$. Curcature and curvature change have no discontinuities and the required limits are complied. Thus, it was verified that the planned trajectories match the theoretical requirements of the machine kinematics.

The planned trajectory is also verified with real field tests. Also the track accuracy is measured. The experimental setup is based on a tractor (CLAAS Axion 840) with steering system (CLAAS S10 with RTK). The vehicle parameters are known with a minimum turning radius of R_{min} = 5.2 m, a maximum steering lock-to-lock time of $t_{steering}$ = 3 s and a constant driving speed v = 6 km h^{-1}. The presented methodology has been implemented in Matlab. A generated turn path is tranferred via USB as reference line to the steering system. This reference line is driven automatically.

The field test is recorded via navigation sensors of the steering system with RTK correction. The recording frequency is defined with 10 Hz. A Matlab script analyses the recording. The quality criterion for path tracking is the cross track error (DLG 2003). It is defined as the distance between recorded position and planned trajectory. Figure 7 shows the computed cross track error. The maximum error is 0.05 m. Especially the connection to the target track is described with an error of 0.01 m. This enables the shown planning method for precise working on the next track.

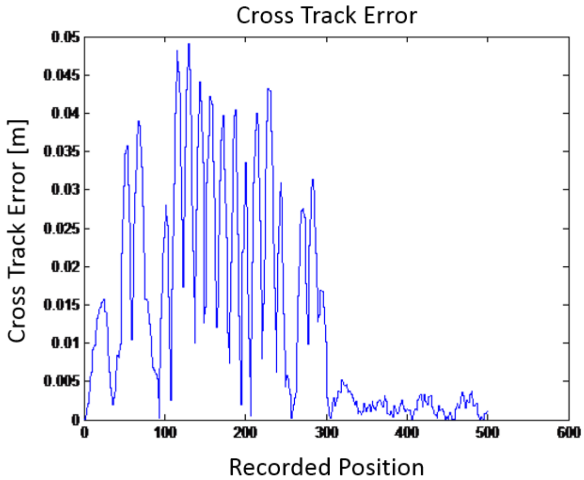

Figure 7: Cross track error between recorded GPS position and planned CC path

Conclusions

The construction of CC-Paths with its base component CC-Circle simplifies turn manoeuvre computation and guarantees feasible trajectories in acceptable computation time without spline interpolation/approximation or other numerical approaches. The initial computed elements circle, straight and clothoid – in shifted or rotated form – can be used for any turn manoeuvre. Extensions, e.g. usage in strip till, must be developed in further steps.

The presented methodoly can be integrated into a steering system and used as headland automation. The driver is relieved and can concentrate on tasks like process optimisation or implement control. Precise track connections enable exact seeding. If no direction changes are planned, the shortest possible path is found and so, fuel can be saved.

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