STRAIGHT LINE TRACKING FOR FOUR WHEELED SKID STEERING VEHICLES

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ABSTRACT

This work treats the problem of tracking lines, defined by two waypoints, with skid steering vehicles. Inspired of how a "good helmsman" would steer a boat onto straight line, a controller structure is developed. Limitations of a skid steering vehicle is considered and compensated for in the controller structure. An experiment has been conducted, and the results are presented.

1. INTRODUCTION

Following straight lines with Unmanned Ground Vehicles (UGVs) can serve many purposes. The motivation for designing and implementing a controller algorithm for a UGV is the ASETA project [1]. This project suggests usage of unmanned four wheeled skid steering vehicles for agricultural work in beet fields.

Driving four wheeled skid steering vehicles, in a beet field, introduces a risk of damaging the crops, e.g. if they are run over or torn up by the wheels when cornering. In order to limit crop damage, the goal is to keep the wheels in between the rows and limit the rotation of the vehicle.

Beet fields can be regarded as straight rows of crops planted with a given distance between the rows. Considering a whole field with this layout, it is suggested that the beet rows are considered as straight lines. Two coordinates describe a straight line segment which the vehicle has to follow until the end of the line segment is reached.

Following the line as closely as possible is important to reduce damage inflicted to the crops. The suggested line tracking is inspired by "good helmsman" principle [2], where the aiming point is changed from the end point, to a point on the line segment. This point is calculated on the run as a function of the current position of the UGV.

The aiming point is used in a controller where angle error and distance to end point is calculated based on current position, heading, and end point. Two separate controllers are used to minimise the angle error and the distance to the end point, by specifying an input angular and linear velocity of the vehicle.

Skid steering vehicles have nonholonomic constraints which implies that they can not move freely in every direction. The vehicle is able to turn on the spot by turning left and right wheel pair in opposite direction of each other. However this can have drawbacks since the field surface is not solid. The crops can get torn up and the vehicle might get stuck. Therefore a constraint is added, to ensure that the wheel pairs are not rotating opposite of each other.

In situations where a wheel pair reaches its maximum angular velocity, a correlation between vehicle rotation and forward velocity occurs. This results in a reduction of both vehicle rotation and forward velocity although they are both individually within the limitations of the vehicle. In order to turn rapidly onto the line, angular velocity is considered more important than linear velocity. The angular velocity is therefore decoupled from the linear velocity by using a kinematic model. The decoupling is designed to achieve the wanted angular velocity by reducing linear velocity if necessary. This implies that the vehicle has better straight line following capabilities, but an increase in the time it takes for the vehicle to reach its destination.

This paper describes the above mentioned methods including a controller structure using them. Finally the results from a practical experiment is presented. In this experiment the described methods are implemented on a specific four wheeled skid steering vehicle requested to run on a straight line.

2. METHODS

The task of navigating a four wheeled skid steering vehicle to a given destination can be conducted using several methods. The vehicle's paths for two different methods are shown in figure 1.

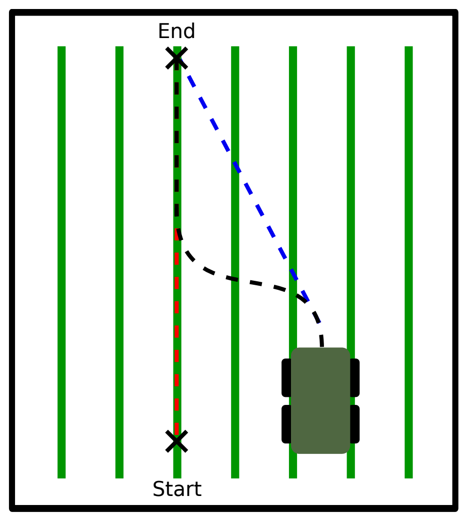

Figure 1: Possible paths of the vehicle using two different control methods.

The blue path is obtained if the vehicle is driving directly to the end waypoint. This method will generally entail in driving on the rows of crops for a longer distance. Introducing a *Start* waypoint, a straight line segment can be defined from the *Start* waypoint to the *End* waypoint. By defining such line segments, the distance driven on the rows of crops can be reduced by following this line. A possible path for the vehicle using a line tracking principle is shown with black in figure 1.

To get the vehicle to follow a straight line, an aiming point on the line segment must be generated. To get the vehicle to reach the end point of the line segment, this aiming point must be placed somewhere between the orthogonal projection of the vehicle onto the line and the end point of the line segment. This situation is illustrated in figure 2.

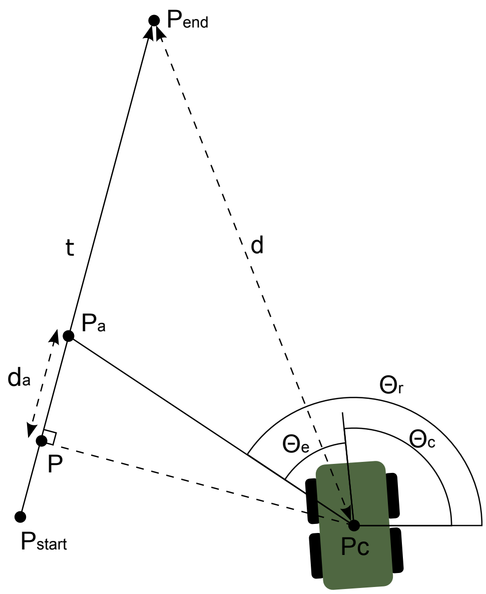

Figure 2: Aiming point and controller input generation.

The orthogonal projection P of current vehicle position P_c onto the line segment t is generated by using vector projection:

$$t = P_\mathrm{end} - P_\mathrm{start} \tag{1}$$

$$P = P_\mathrm{start} + \left(\frac{(P_\mathrm{c} - P_\mathrm{start})^T \, t}{t^T t} \right) t \tag{2}$$

The aiming point P_a is specified by aiming some distance d_a ahead of the projection point P:

$$P_\mathrm{a} = P + d_\mathrm{a} \frac{t}{||t||_2} \tag{3}$$

The distance d_a can advantageously be chosen as a fraction $\frac{1}{c_\mathrm{h}}$ of the distance from the projection point P to the end point P_end, where c_h is a positive constant. By choosing the distance in this way the aiming point will converge to the actual end point of the line segment when the vehicle approaches this.

Choosing the aiming distance as a fraction of the distance to the end point does however give rise to some problems. When the distance from the projection point to the end point is large, d_a will be large as well. A large d_a will imply that the vehicle must drive for a longer distance before it converges to the line, resulting in more damage inflicted to the crops.

To prevent aiming too far ahead, it is suggested to aim a constant distance k ahead. Doing so, the convergence to the line does only depend on the orthogonal distance from the line, and not on the distance to the end point. Aiming a constant distance ahead does however give rise to convergence problems at the end point of the line segment, since the aiming point does not converge to this.

To obtain the advantages of both strategies it is suggested to combine them. Using the first mentioned strategy, when close to the end point of the line segment, ensures that the aiming point converges to the end point. At long distances from the line segment's end point, the second mentioned strategy is used:

$$d_\mathrm{a} = \begin{cases} \frac{||P_\mathrm{end} - P||}{c_\mathrm{h}} & \text{for } ||P_\mathrm{end} - P||_2 \le l \\ k & \text{for } ||P_\mathrm{end} - P||_2 > l \end{cases} \tag{4}$$

Where:

l is the threshold between the aiming strategies

To make sure that no discontinuity occurs in the distance d_a aimed ahead of the projection point, the parameters c_h, k, and l must be chosen such that the two used strategies result in the same d_a at the threshold l. The relation between the parameters is found by setting $||P_\mathrm{end} - P|| = l$ in (4), and equating the two ways of choosing d_a:

$$k = \frac{||P_\mathrm{end} - P||_2}{c_\mathrm{h}} = \frac{l}{c_\mathrm{h}} \tag{5}$$

Having generated an aiming point P_a, a heading error Θ_e can be calculated. From figure 2 it is seen that this error is calculated as:

$$\Theta_\mathrm{e} = \Theta_\mathrm{r} - \Theta_\mathrm{c} \tag{6}$$

Where:

Θ_r is the reference angle to the aiming point

Θ_c is the current heading of the vehicle

Having a heading error Θ_e and a distance d to the line segment end point (see figure 2), the controller structure shown in figure 3 is suggested to minimise the heading error and distance to end point.
The heart of the control structure is the *Reference angle calculator*, generating the aiming point P_a and thereby the reference angle Θ_r. The *Distance calculator* and *Angle error calculator* calculate d and Θ_e respectively from the references and the current heading and position of the vehicle. The two controllers are used to minimise the error angle Θ_e and the distance to the end point P_end.

The *Linear velocity limiter* block is inserted to decouple the angular velocity from the linear velocity inputs of the robot. The *Angular velocity limiter* block is used to limit the rotation of the robot to reduce the damage done to the field and crops.

2.1 Kinematic model of a skid steering vehicle

A kinematic model is used in order to specify the relation between angular and linear velocity of vehicle and the velocities of the wheels. This model is based on derivations in [3]. When deriving the model, the following assumptions have been made:

- Longitudinal wheel slippage is neglected
- Left wheel pair is running with equal angular velocity
- Right wheel pair is running with equal angular velocity
- The centre of mass (COM) is located with equal transverse distance to the right and left wheels.

The relationship between the wheel velocity and the angular and linear velocity is derived to be as follows:

$$v_\mathrm{L} = v_\mathrm{fwd} - \omega c \tag{7}$$

$$v_\mathrm{R} = v_\mathrm{fwd} + \omega c \tag{8}$$

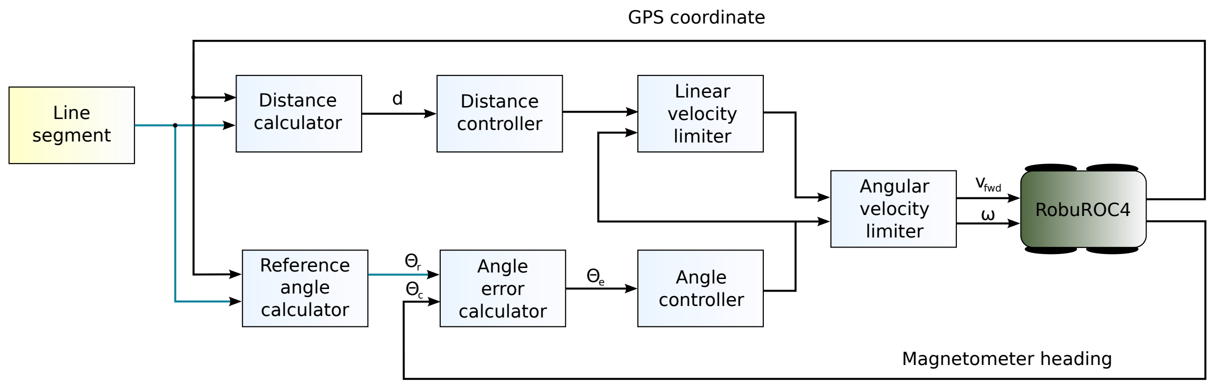

Figure 3: Control structure used to navigate the vehicle.

Where:

v_{fwd} is the longitudinal linear velocity of the vehicle
ω is angular velocity of the vehicle
v_{L} is the longitudinal linear velocity on the left wheels
v_{R} is the longitudinal linear velocity on the right wheels
c is the transverse distance from the COM to the wheels

Rewriting (7) and (8) yields the following equations for the linear and angular velocity of the vehicle.

$$v_{\mathrm{fwd}} = \frac{v_{\mathrm{R}} + v_{\mathrm{L}}}{2} \tag{9}$$

$$\omega = \frac{v_{\mathrm{R}} - v_{\mathrm{L}}}{2c} \tag{10}$$

2.2 Robot input decoupling

In skid steering vehicles it is assumed that the independent wheels have a limited maximum velocity called $v_{\max}$. This maximum wheel velocity is inserted in (7) and (8) as forward linear velocity v_{fwd}. Applying an angular speed greater than zero ($|\omega| > 0$) now causes the velocity on one of the wheel pairs to be greater than the maximum wheel velocity. Here exemplified for the right wheel pair with positive angular velocity.

$$\begin{aligned} v_{\mathrm{R}} &= v_{\mathrm{fwd}} + \omega c \\ &= v_{\max} + \omega c > v_{\max} \quad (\text{for } \omega > 0) \end{aligned}$$

In the case where the wanted wheel velocity is faster than its maximum, it is assumed that the wheel velocity of that wheel pair is simply saturated to the maximum wheel velocity. From (9) and (10) it is seen that a saturated wheel velocity will cause both the linear and angular velocities to be reduced.

The reduction in the linear velocity increases the time it takes to reach the target while a reduction in angular velocity reduces the manoeuvrability and thereby the precision. The achievement of precision when driving is considered most important in order to limit crop damage. It is therefore chosen to decouple the angular velocity from the linear velocity by limiting the linear velocity, such that the wanted angular velocity always can be obtained.

The linear velocity of the vehicle must therefore be reduced to some maximum velocity (v_{fwdMax}) depending on the wanted angular velocity. An equation for the maximum linear velocity is deduced from (7) and (8). By setting the speed of the wheels (v_{R} and v_{L}) to the maximum wheel speed $v_{\max}$ and the forward velocity v_{fwd} to the maximum allowed forward velocity v_{fwdMax}, (7) and (8) reduces to:

$$\begin{aligned} v_{\max} &= v_{\mathrm{fwdMax}} - \omega c \quad (\text{for } \omega < 0) \\ v_{\max} &= v_{\mathrm{fwdMax}} + \omega c \quad (\text{for } \omega > 0) \\ &\Downarrow \\ v_{\max} &= v_{\mathrm{fwdMax}} + |\omega c| \end{aligned} \tag{11}$$

From (11) the following equation for the maximum linear velocity is derived:

$$v_{\mathrm{fwdMax}} = v_{\max} - |\omega c| \tag{12}$$

By saturating the linear velocity input to the vehicle v_{fwd} to v_{fwdMax} specified in (12), it is ensured that the wanted angular velocity ω is obtainable, given that ω is within the limitations of the vehicle.

2.3 Limit rotation to reduce crop damage

As a consequence of the skid steering construction, the vehicle is capable of turning on the spot by reversing the velocity on one wheel pair compared to the other. Turning on the spot causes transverse skid on the wheels. When driving in a field this transverse skid can be a problem since it might cause the vehicle to tear up crops or get stuck in the field. It is therefore chosen to limit the velocity of the wheels to some minimum wheel velocity v_{wheelMin}. This limitation is made using the kinematic model. As an example, a left turn is considered. Limiting v_{L} to v_{wheelMin} in (9) and (10), gives the following:

$$v_{\mathrm{fwd}} = \frac{v_{\mathrm{R}} + v_{\mathrm{wheelMin}}}{2} \tag{13}$$

$$\omega = \frac{v_{\mathrm{R}} - v_{\mathrm{wheelMin}}}{2c} \tag{14}$$

Combining (13) and (14) by deriving v_{R} in (13) and inserting it in (14) yields (15).

$$\omega = \frac{v_{\mathrm{fwd}} - v_{\mathrm{wheelMin}}}{c} \tag{15}$$

Equation (15) describes the situation where the combination of ω and v_{fwd} results in exactly $v_{\mathrm{L}} = v_{\mathrm{wheelMin}}$. The value of ω can be interpreted as a maximum allowed value angular velocity for a specified v_{fwd}, and choosing smaller values causes $v_{\mathrm{L}} > v_{\mathrm{wheelMin}}$. Equation (15) is used to generate an equation which must be fulfilled to obtain $v_{\mathrm{L}} > v_{\mathrm{wheelMin}}$ in a left turn:

$$\omega \leq \frac{v_{\mathrm{fwd}} - v_{\mathrm{wheelMin}}}{c} \tag{16}$$

The same equations can be derived for right turns as well. Combining the constraints for the left and right turns results in the following combined constraint which the inputs to the robot must comply with to prevent wheel velocities below v_{wheelMin}.

$$|\omega| \leq \frac{v_{\mathrm{fwd}} - v_{\mathrm{wheelMin}}}{c} \tag{17}$$

Since it is not desired to increase v_{fwd} to make (17) valid, it is chosen to reduce ω.

3. RESULTS

To test the performance of the proposed controller principle, an experiment is carried out. In this experiment a four wheeled skid steering vehicle is placed at a distance from a line segment, and is requested to navigate to the end point of the line segment.

The controlled skid steering vehicle used for the experiment is a RobuROC4. The sensor used by the controller to determine the position of the vehicle is a GPS receiver. A magnetometer is used to determine the heading. The used hardware is listed in table 1.

Component	Model no.
Vehicle	Robosoft - RobuROC4
GPS	Ashtech - MB100
Magnetometer	Ocean Server - OS5000-US

Table 1: Components used in the experiment.

Table 2 contains the values of the parameters mentioned in the methods section. The parameters regarding the RobuROC4 are determined by model tests and specifications from its data sheet. The angle and distance controllers are both P-controllers, with gains k_{pAng} and k_{pDist} respectively. The controller gains are determined through analysis of the RobuROC4 dynamics. The parameters regarding the aim generation are determined from simulations and considerations on the limitations and dynamics of the RobuROC4.

The Ashtec-MB100 GPS uses Real Time Kinematics (RTK) technology to obtain a precision down to 1 cm [4]. Since this is the most precise way to determine the position of the vehicle in run time, the GPS output is used in the experiment to determine the current position of the vehicle.

In the following results, the GPS coordinates (latitude and longitude components) have been converted into UTM coordinates [5]. Additionally an offset has been removed from the converted coordinates, such that the initial position of the vehicle is (0,0).

In figure 4 the position of the vehicle is plotted alongside with the line segment to be followed.

	Parameter	Value	Unit
RobuROC4:	v_{max}	2.59	m/s
	v_{wheelMin}	0.2	m/s
	c	0.34	m
Target generation:	k	2	m
	c_{h}	2	-
	l	4	m
Controller gains:	k_{pAng}	2	-
	k_{pDist}	1	-

Table 2: Controller parameters.

As seen in the figure, the vehicle is initially placed at a distance from the line segment. The change of position in the beginning of the run indicates that the vehicle starts almost parallel to the line segment. First the vehicle drives slightly away from the line to follow before it turns towards the line. Before the vehicle reaches the line, it changes direction towards the end point, and thereby limits the overshoot. The vehicle then follows the line until it reaches the end point. From this it is seen that the implemented control structure enables the vehicle to turn onto a line segment and follow it to the end point.

To show the performance of the controller structure, the orthogonal distance from the current position of the vehicle to the line segment is calculated. This distance is shown in figure 5.

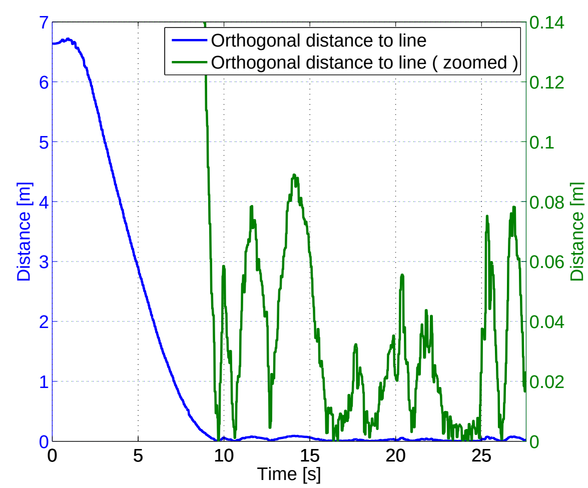

Figure 5: Orthogonal distance from current position to the line. The green graph is a zoomed version of the blue one.

This figure shows that the vehicle reaches the line after around 10 s. From time 10 s and onwards the orthogonal distance from the vehicle to the line is below 90 mm. Additionally it is seen that the distance is below 40 mm in the majority of the time in the interval from 15 s to 25 s.

4. DISCUSSION

From the results is can be concluded that using the proposed controller structure makes it possible for the vehicle to drive onto a straight line given by two waypoints and follow the line to the end of the line segment.

Using a RobuROC4 in a beet field with a spacing of 0.5 m between the rows [6] and a row width of 100 mm, allows the vehicle to diverge up to 55 mm from the line segment before hitting a row. As shown in the results the current setup is only capable of obtaining a precision of 90 mm. Due to the

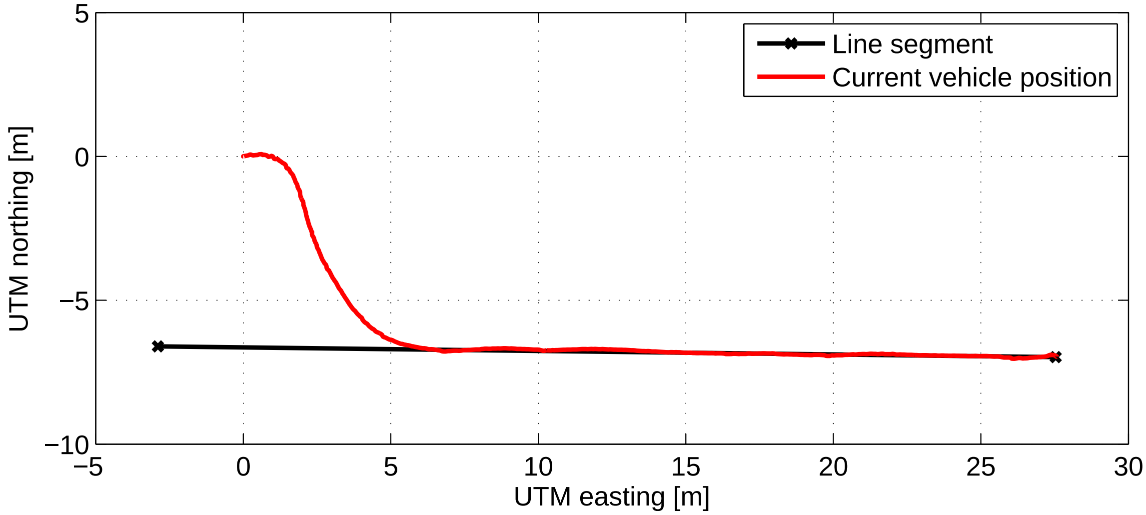

Figure 4: Path of the vehicle during the experiment.

orthogonal distance of 90 mm it can not be assured that the vehicle will keep in between the rows, and thereby the vehicle will cause damage to the crops.

Analysis on the sensor data from the magnetometer indicates a problem that may have influence on the deviations shown in figure 5. Due to degaussing of the magnetic field sensors, the calculated heading of the vehicle is periodically off by up to 12° for 0.2 s with a period of 3 s. These faulty readings forces the vehicle to turn, and therefore results in an increase of the orthogonal distance to the line. This problem makes it difficult to determine the actual limitations of the controller structure. The problem with the faulty magnetometer reading should therefore be solved before trying to make improvements of the controller structure.

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