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Enhancement of Turning Accuracy by Path Planning for Robot Tractor

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ABSTRACT

Turning algorithm for a robot tractor was developed in this paper. Two types of turning paths were created by applying third-order Spline function; forward turning and switch-back turning. The constraints relating to the tractor characteristics, minimum turning radius and maximum steering speed, were introduced for creating a feasible turning path. The turning path was recalculated while created path didn't meet these constraints.

Validity of the constraints was confirmed by a computer simulation. Developed algorithm was installed in the robot tractor with an RTK-GPS and a FOG and tested at field. It showed higher following accuracy in comparison to conventional method.

KEYWORDS. Turning path planning, Spline function, Motion constraints, Forward turning, Switch-Back turning

INTRODUCTION

The final goal of this study is to develop an autonomous tractor system engaged in all type of operations at fields. The robot tractor adopted an RTK-GPS and a FOG as navigation sensors was developed in previous research (Kise et al., 2001). It had performed autonomous operation with less than 10 cm error at field, but more than 50cm error had been occurred in turning process.

The turning algorithm developed in previous research was; when the robot makes turn to near left pathing 1) turning left with maximum steering angle, 2) backing with 0 of steering angle until required position calculated by measured turning radius at step 1), 3) turning left with maximum steering angle. This method could compensate variability of minimum turning radius of a vehicle caused surface condition by adjusting backward distance. But it sometimes arose more than 50cm of lateral displacement between final position on turning and next desired path due to fluctuation of tire-soil surface interaction.

Turning path creation algorithm using Spline function was developed in this paper. The constraints relating to the tractor characteristics, minimum turning radius and maximum steering speeds, were introduced for creating a feasible turning path. The turning path was recalculated while created path didn't meet these constraints. Two types of turning methods were developed; forward turning, and switch-back turning.

ALGORITHM OF TURNING PATH CREATION

<u>Motion Constraints</u>

1) Minimum turning constraint

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Desired path is represented as a subset of the points referred to as "navigation points". Both a straight path and a curved path can be depicted because desired path are exposed as a set of points.

The minimum turning radius constraint requires radiuses of curvature $r(\omega)$ of all navigation points to fulfill below equation;

$$r(\omega_i) \bullet R_{\min} \qquad (0 \le i < N) \tag{1}$$

Where, $R_{\min}$ is minimum turning radius of a vehicle, ω_i is i th navigation point, and N is the number of navigation points.

2) Maximum steering speed constraint

Maximum steering constraint is defined as follows;

$$|u_r(\omega_i)| \le U_{\max} \tag{2}$$

$$u_r(\omega_i) = \frac{\delta_d(r(\omega_{i+1})) - \delta_d(r(\omega_i))}{\Delta t} \tag{3}$$

$$\Delta t = \frac{\|\omega_{i+1} - \omega_i\|}{V} \tag{4}$$

Where, $u_r(\omega_i)$ is required steering speed for steering from steering angle $\delta_d(r(\omega_i))$ decided by $r(\omega_i)$ to $\delta_d(r(\omega_{i+1}))$, $U_{\max}$ is maximum steering speed of a vehicle, Δt is the interval when vehicle moves from ω_i to ω_{i+1}, and V is travel speed of the vehicle.

Maximum steering speed constraint is fulfilled by $u_r(r(\omega_i))$ to be smaller than maximum steering speed of a vehicle.

<u>Forward Turning</u>

Figure 1 shows the algorithm of path creation for forward turning in case of left turning. Point A and Point F represent the beginning of turning and the end of turning, respectively. Point A, B, C, D, and E are applied third-order Spline function as predetermined middle points called knots. Point E and F is connected by straight line, and a vehicle is able to approach the next path in the range of E to F. w is the width of paths and d is the length between E and F.

Forward turning is composed of three circles. Circle Q_1 tangents with last desired path at point A, Q_3 tangents with next desired path (y axis) at point E, and Q_2 tangents with Q_1 and Q_3. The turning path fulfilling the constraints is created by changing the radiuses of these circles according to the constraints. **Figure 2** shows the flowchart of path creation of forward turning. The radiuses of the circles including the navigation points not fulfilling minimum turning radius constraint is enlarged 10cm and turning path is recalculated until the constraint is fulfilled. On

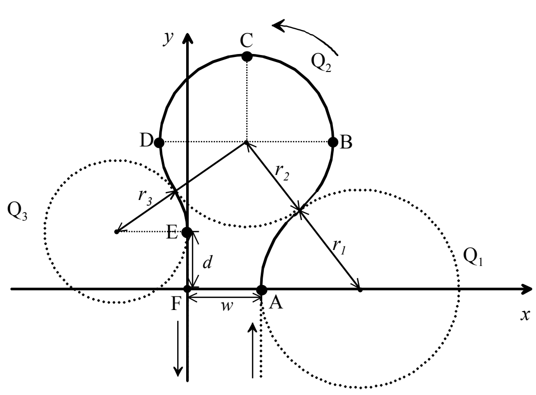

Figure 1. Algorithm of path creation for forward turning in case of left turning

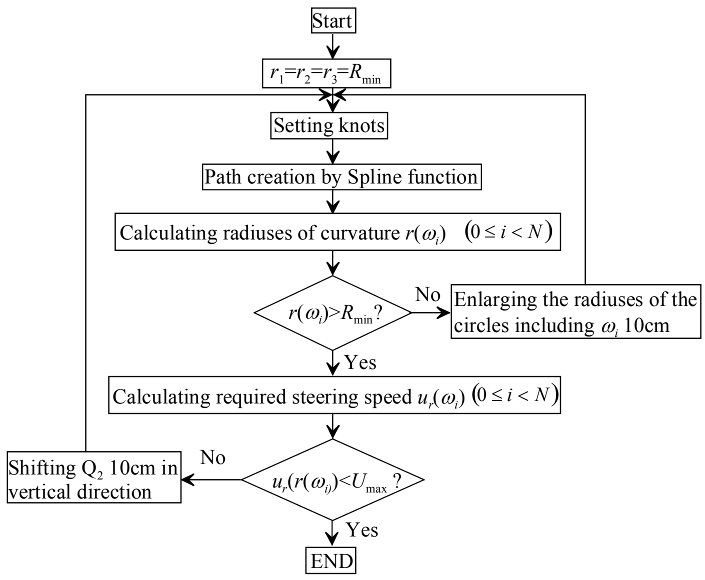

Figure 2. Flowchart of path creation of forward turning

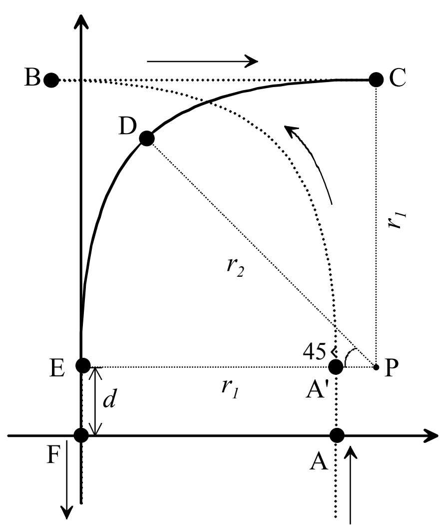

Figure 3. Algorithm of path creation for switch-back turning in case of left turning

the other hand, Q2 is shifted 10cm in vertical direction when any navigation points don't fulfill the maximum steering speed constraint. In case where all navigation points fulfill both constraints, the created path is regarded as feasible path.

Switch-Back Turning

Figure 3 shows the algorithm of path creation for switch-back turning. Point A and Point F are the beginning of turning and the end of turning, respectively, and segment B-C represents backward distance. Point D is the middle point of the arch of the circle CE, and C, D, and E are applied Spline function as knots. r_1 is enlarged 10cm in cases where any navigation points don't fulfill the minimum turning radius constraint. In case where the maximum steering speed constraint is not fulfilled, r_2 is enlarged 10cm. The path between A and B is generated by inverting CF that fulfills both constraints.

COMPUTER SIMULATION

Vehicle dynamics model

The vehicle dynamics model using computer simulation is described by a simple bicycle model;

$$\begin{bmatrix} \dot{\beta} \\ \dot{\gamma} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -\frac{2(K_f + K_r)}{MV} & -1-\frac{2(l_f K_f - l_r K_r)}{MV^2} & 0 \\ \frac{-2(l_f K_f - l_r K_r)}{I} & \frac{-2(l_f^2 K_f + l_r^2 K_r)}{IV} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ \phi \end{bmatrix} + \begin{bmatrix} \frac{2K_f}{MV} \\ \frac{2l_f K_f}{I} \\ 0 \end{bmatrix} \delta \tag{5}$$

$$\dot{x} = V \sin(\phi + \beta) \tag{6}$$

$$\dot{y} = V \cos(\phi + \beta) \tag{7}$$

β: slip angle of COG, γ: angular velocity, ϕ: vehicle heading, $(x, y)^T$: COG position with reference to GPS coordinate

Where, K_f and K_r are cornering stiffness of front and rear tires, respectively, l_f and l_r are length between COG and each of front and rear axles, m is vehicle mass, and I is mass moment of inertia of the vehicle about the vertical axis.

The vehicle considered in this simulation is arbitrary vehicle, and following values were adopted as vehicle parameter.

K_f=160N/deg, K_r =260N/deg, l_f =1.6m , l_r=0.7m • m=3200kg, I=1000kg • m^2 (8)

In order to calculate maximum steering speed constraint, steering angle of a vehicle has to be represented as a function of turning radius. The steering angle of a vehicle $\delta_d(r(\omega_i))$ is represented by,

$$\delta_d(r(\omega_i)) = (1 - cV^2)\frac{l_f + l_r}{r(\omega_i)}, \; c = \frac{m}{2l^2}\frac{l_f K_f - l_r K_r}{K_f K_r} \tag{9}$$

And also minimum turning radius of a vehicle $R_{\min}$ is required for calculating minimum turning radius constraint, and represented by

$$R_{\min} = (1 - cV^2)\frac{l_f + l_r}{\delta_{\max}} \tag{10}$$

Where, $\delta_{\min}$ is maximum steering angle of a vehicle.

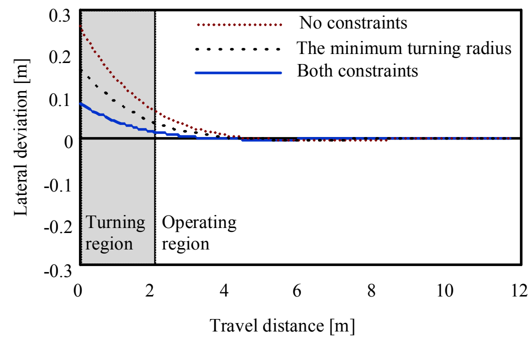

Figure 5. Comparison of turning accuracy by applying different constraints on simulation of forward turning

Simulation Results

Guidance simulations are conducted under three types of paths; the path applied both constraints; the path applied the minimum steering angle constraint alone; the path without constraints; The guidance with no constraint appears that the radius of curvature of created path is too small for the vehicle to follow it, as shown in **Figure 4**. On the other hand, the guidance with the minimum turning constraint and both constraints seems to be performed with desired accuracy, but the guidance with both constraints shows better accuracy at the end of the turning than that with single constraint, as shown in **Figure 5**.

Switch-back turnings reveal also similar results to forward turnings.

EXPERIMENTAL RESURLT

Parameter Identification of the Tested Vehicle

Eq. (8), considered arbitrary vehicle is unable to apply actual vehicle. For identification of the parameters of the tested vehicle, constant steering turning test was conducted at the field. Radiuses of constant steering turning were obtained at eight steps of steering angle (-40•-30•-20•-10•10•20•30•40 [deg]) and four steps of travel speeds (0.35, 0.55, 0.83, 1.30 [m/s]).

In order to calculate the maximum steering speed constraint, steering angle must be represent as function of turning radius, like Eq. (9). Power function is introduced in an empirical equation for representing steering angle.

Table 1. Distance of head land and lateral deviation at end of turning

Travel speed [m/s]	Forward turning				Switch-back turning				
	0.35	0.55	0.83	1.30	0.35	0.55	0.83	1.30	0.55*
Distance of head land [m]			13.6			5.88			54
Lateral deviation at end of turning [cm]	14	17	20	16	15	17	28	27	74

*Conventional method

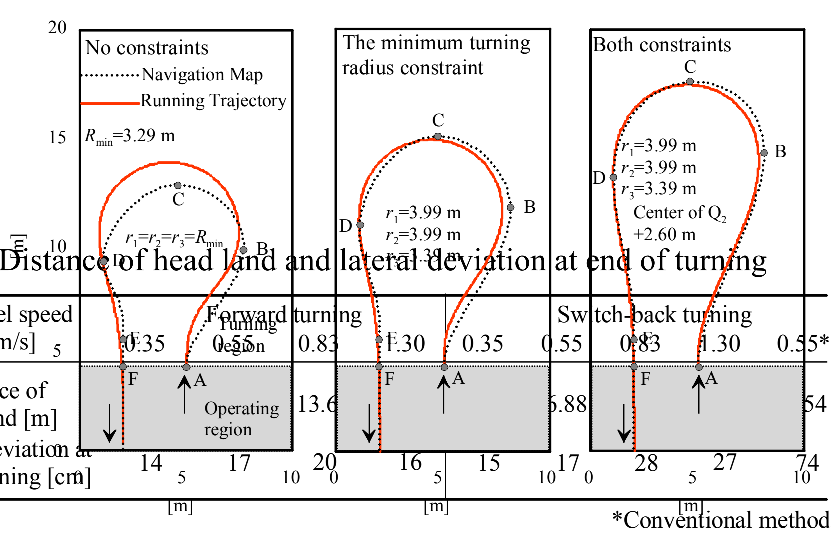

Figure 4. Simulation results of forward turning

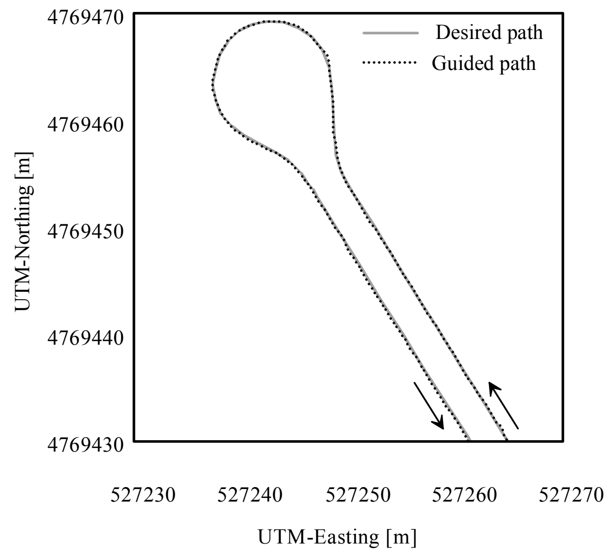

Figure 6. Guided path and desired path of forward turning at 1.3 m/s

Guidance Result of Forward Turning

Figure 6 shows the guided path and the desired path of forward turning at 1.3 m/s. Guided path depicts almost same trajectory with desired path, and it proves feasibility of created path. **Table 1** lists that required distances of headlands and lateral deviations at the end of turning in each travel speed. Result of them indicates that lateral deviations are not affected by travel speed, and required distances of head lands are less than 16m at all travel speeds.

Guidance Result of Switch-Back Turning

Figure 7 shows the guided path and the desired path of switch-back turning at 0.55 m/s. Maximum lateral deviation of 30cm was occurred at backward segment, but r.m.s. error of all turning routine was 20cm, and the error at the end of turning was 17cm.

Switch back guidance was compared with conventional method described in the introduction, as shown in **Figure 8**. The lateral deviation of developed method in this paper `didn't exceed 20cm at operating region, while conventional method gone to 70cm error. The lateral deviations and distances of the head lands at each travel speeds are listed at **table 1**. Compared with 0.35m/s and 0.55m/s, 0.83m/s and 1.35m/s were larger with the lateral deviation of 28cm and 27cm. The distances of head lands that are almost same over all travel speeds, which indicate that increasing travel speed doesn't required enlargement of head land on tested robot tractor.

CONCLUSION

Two types of turning path creation algorithms for forward turning and switch-back turning are proposed.

Third-order Spline function is used for path creation. The constraints relating to the tractor characteristics, minimum turning radius and maximum steering speeds, were introduced for

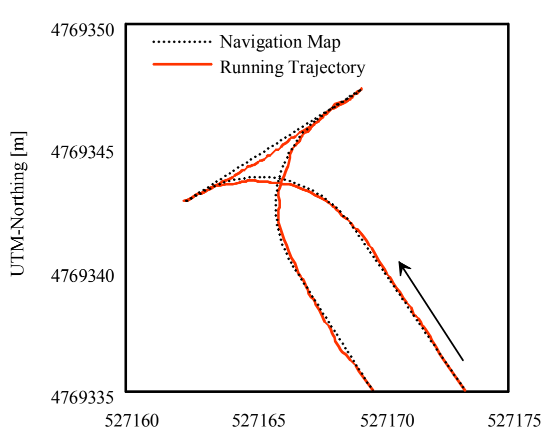

Figure 7. Guided path and desired path of switch-back turning at 1.3 m/s

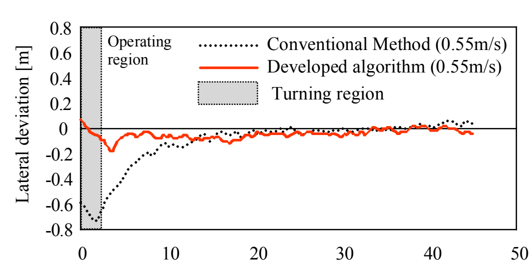

Figure 8. Comparison between developed switch-back turning and conventional one

creating a feasible turning path.

The better results have been obtained in the simulation by applying both constraints comparing than no constraints and single constraint.

The result of installing developed method to the robot tractor is to make lateral deviation at the end of turning less than 20 cm at all travel speed.

Compared to conventional method, developed switch-back turning algorithm reduce lateral deviation at the end of turning by more than 50cm.

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