A Fuzzy Path Preview Algorithm for the Rice Transplanting Robot Navigation System

Zhiyan Zhou
College of Engineering, South China Agricultural University, Guangzhou 510642, China
Email: zyzhou@scau.edu.cn

Zhigang Zhang and Xiwen Luo
College of Engineering, South China Agricultural University, Guangzhou 510642, China
Email: {zzg208, xwluo}@scau.edu.cn

***Abstract*—Path preview is the key to realizing automatic navigation control that can guide the navigational direction of the vehicle trace. The preview point must be regulated dynamically according to the predetermined navigational features of the actual path preview control to obtain the ideal path trace result. Based on the "preview follower theory" combined with the driver's experience and utilizing the Matlab (The MathWorks, Inc., Natick, Massachusetts, USA) fuzzy control toolbox, a fuzzy algorithm of the preview point has been proposed in the paper. The navigation control system embedded in the path planning and preview control algorithm has been applied in the experiment to trace a predetermined navigational straight way, 90°curve and arc way to operate a rice transplanting robot. The results showed that the lateral DRMS (distance root mean square error) of the straight trace is approximately 0.33 m, and the maximum error is approximately 0.71 m; the lateral DRMS of the 90°curve trace is approximately 0.73 m, and the maximum error is approximately 1.85 m; the lateral DRMS of the arc way trace is approximately 1.03 m, and the maximum error is approximately 2.56 m; and the total mean error is approximately 0.6 m. According to the outcome of the experiment, the relevant algorithm can basically meet the requirements of rice transplanting robot guidance.**

***Index Terms*— Automatic navigation control, Path preview, Fuzzy, Rice Transplanting Robot, Navigation system**

I. INTRODUCTION

The following three questions must be answered concerning an agricultural machine automatic navigation control system for the machine to be operated with predetermined navigational safety and accuracy, "Where is it now?", "Where to go now?" and "How to go now?"[1-5]. Path preview control is the key for the second question --- "Where to go now?" which guides the direction of the vehicle trace navigation. At first, the best front distance according to the vehicle attitude and the predetermined navigation should be calculated. Next, the front distance should be taken as a reference for deciding the current preview point (the point of the target) of the navigation and the direction from the current point to the preview point as the objective of the navigation. The yaw is calculated from the current vehicle navigation and the objective navigation. Controlling the curve on the basis of the yaw answers the question "Where to go now?"[6]

The preview point must be regulated dynamically according to the navigation features in the actual path preview control system to obtain the ideal path trace result [7, 8]. Research on path preview control has been conducted since the 1960s [9]. However, there are lots of differences of the Path Preview algorithms between off-road vehicle and indoor mobile robot [10, 11] and industrial robot [12]. Peng, H. et al have proposed the preview control method combined with front feed and feedback and introduced path curvature into the front feed circuit to improve the path trace effect of the entire system [9]. Park, J. et al. (1996) hypothesized that the curve angle of the vehicle is the function of the driving speed, and the simulating outcome displays that the front model of the driver meets well with the requirement of that the highway vehicle automatically controls the driving speed[13]. Thomas Bell (1999) has used the following vehicle position prediction to make preview control when controlling the agricultural vehicle automatic, and the predicting model of the correspondent vehicle position was established, and the control of the current period was calculated by predicting the available positions in the future periods[14]. Zhang Q. et al (2004) determined two preview front distances when designing the navigational preview control of the unmanned tractor. One distance is the navigational trace front distance, and the other is the front distance to drive safety, which sets up the front distance table based on the vehicle speed, the path section curvature, the gear-box shifts and shifting time[15]. Gao Zhenhai et al (2002) established the driver

Manuscript received xx x, xxxx; revised xx x, xxxx; accepted xx x, xxxx.

Project supported by the 863 high-tech Projects of China and National Science and Technology Support Program (Project No.: 2012AA101901-3 and 2011BAD20B06), the Science and Technology Foundation of Ministry of Education of China (Project No.: 212128) and the Scientific and technological innovation projects of higher education institutions in Guangdong Province of China (Project No.: 2012KJCX0023)

Corresponding author: Xiwen Luo (xwluo@scau.edu.cn).

doi:10.4304/jsw.9.4.881-888

direction control model according to the "preview follower theory" and made a relevant simulation; the results indicated that the model can guide the vehicle curve movement at the lower speed and higher speed [16]. Li Qingzhong et al (2002) state that the vehicle control system is a typical delayed, nonlinearity and unstable system, and there is an obvious prediction for preview control that is better than the traditional control algorithm that relied on the information feedback for control, combined with expert driving experience and rule and PID control through the simulating of artificial intelligence in driving. The auto-regulated intelligent PID preview control method based on the rule has been designed according to the path curve degree and the advancing speed of the vehicle[17].

According to the "preview follower theory" combined with driving experience, utilizing the Matlab fuzzy control toolbox, a fuzzy algorithm of the preview point has been proposed in the paper to realize the dynamic auto-regulation of the preview point in the path preview control of the RTR (Rice Transplanting Robot),and to improve the precision of the path trace.

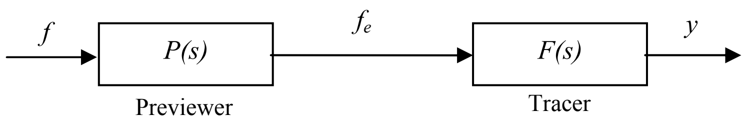
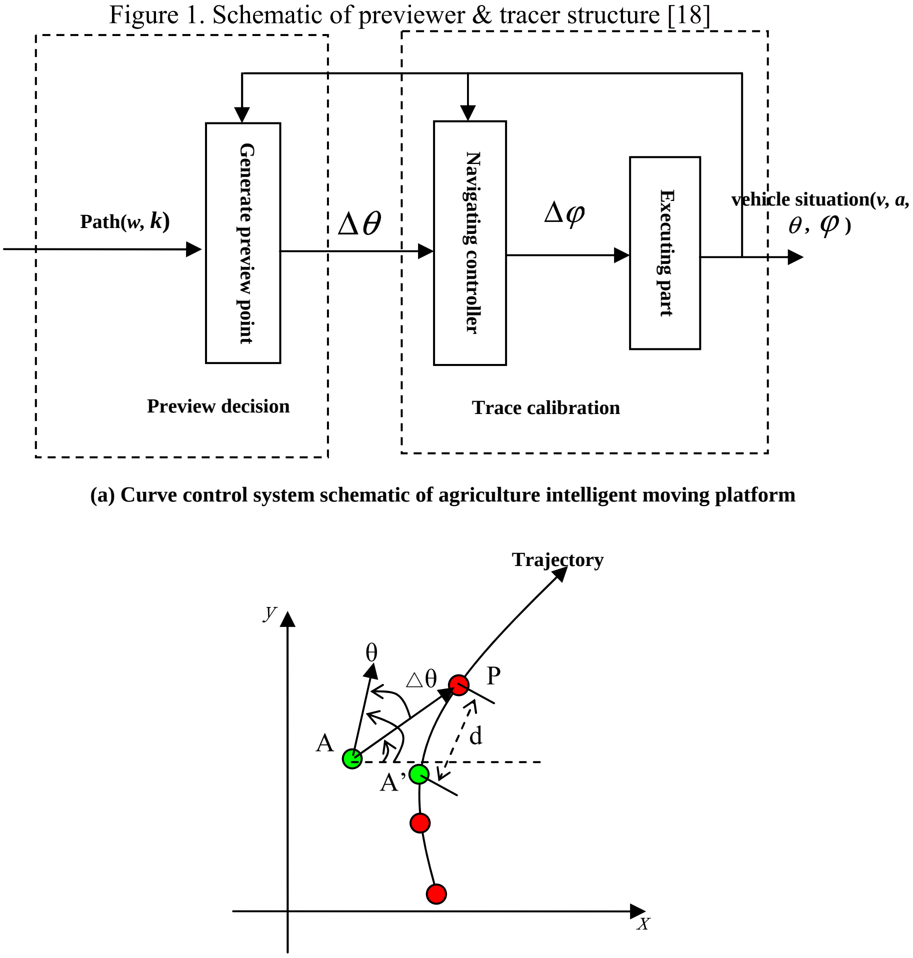


Figure 1. Schematic of previewer & tracer structure [18]



(a) Curve control system schematic of agriculture intelligent moving platform

(b) Schematic to generate the preview point

Figure 2. Navigational preview control principle of the Rice Transplanting Robot

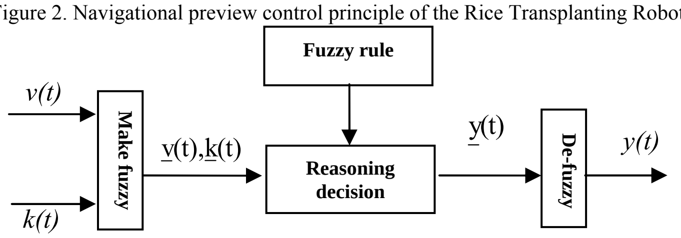


Figure 3. Principle of the preview fuzzy generator

II. Fuzzy Algorithm of the Path Preview

A. Preview Control Principle of the Rice Transplanting Robot

According to the “preview follower theory”, the driving operation of the driver can be taken as a system that parallels a previewer and a tracer, as shown in Figure 1. The previewer is the decision stage of the driver (information perception→decision), and the tracer is equal to the calibrating stage of the driver [16, 18, 19]. The navigational control system of the agriculture intelligent moving platform is an intelligent control system substantially to replace the driver. As shown in Figure 2(a), in the preview stage, the system finds the closest point A’ of the current vehicle position A on the predetermined trajectory and later decides the best front distance *d* according to the vehicle position (the vehicle speed *v*, the acceleration *a*, the navigation θ, the angle of the front wheel φ etc), the road situation (width *w* and curvature *k*)). The system then generates preview point P on the trajectory, the angle of the line connecting the current point A and the preview point P and the current navigational direction of the moving platform; θ is the yaw angle $\Delta\theta$ (as shown in Figure 2b); In the trace stage, a curve control $\Delta\varphi$ is generated by the navigational controller according to the yaw angle $\Delta\theta$, which controls the vehicle to approach the predetermined navigation.

The driver is not certain about the road curvature and the current vehicle speed when deciding the preview, and the fuzzy decision is made based on the long term cognitive driving practice; e.g., the preview should be slightly longer because the current speed is very fast; the speed should be slightly slower because the road is very curved; and/or the preview should be slightly longer as much as possible to understand the information around the curve in the road. The preview decision is fuzzy, and the fuzzy theory is used to research the auto-regulated dynamic calculation of the preview point.

Mamdani is a fuzzy logic system with a fuzzy generator (make fuzz) and the fuzzy eliminator (Defuzzy), that is broadly used in engineering. The Mamdani fuzzy logic system was used to design the fuzzy generator of the preview point in the paper, as shown in Figure 3.

B. Fuzzy Status and the Universe of Discourse of the Input & Output Language Variable

As shown in Figure 3, the fuzzy generator of the preview point is a system with double input and single output; the input language variable is the vehicle speed *v(t)* at *t* and the road mean curvature *k(t)*, and the output language variable is the preview front distance *y(t)* at *t*.

Vehicle speed *v(t)* is described by five fuzzy “shifts”, “Very Low, Low, Medium, High, and Very High”, and the marks of the correspondent fuzzy subclasses are “*VL, L, M, H, and VH*”, and the universe of discourse is selected as [0, 5] (*m/s*) according to the normal operating speed of the agriculture intelligent moving platform.

As shown in Figure 4, the calculating formula $\overline{MM'}$ mean curvature *k(t)* at *t* is:

$$k(t)=\left|\frac{\Delta\alpha}{\Delta s}\right| \tag{1}$$

The mean curvature k(t) is described by five fuzzy “shifts”, “Very Small, Small, Medium, Big, and Very Big”, and the marks of the correspondent fuzzy subclasses are “*VS, S, M, B, and VB*”, and the universe of discourse is selected as [0, 0.5] (*1/m*) according to the normal road situation and the minimum curve radius of the agriculture intelligent moving platform.

The front distance y(t) is described by five fuzzy “shifts”, “Very Near, Near, Medium, Far, and Very Far”, and the marks of the correspondent fuzzy subclasses are “*VN, N, M, F, and VF*”, and the universe of discourse is selected as [3, 15] (*m*).

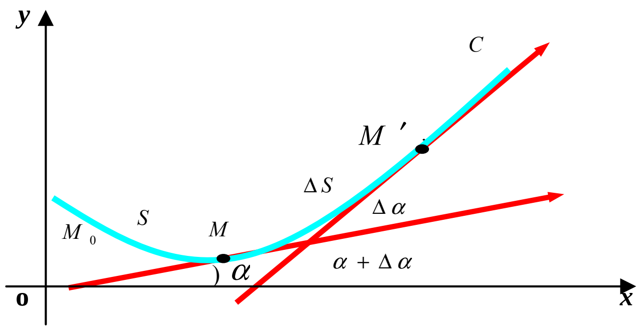


Figure 4. Calculation of the path section mean curvature

C. Determine the Subjective Function of Each Fuzzy Collection

In practice, the most common membership functions are the gauss function and the triangle function [20, 21]. For the convenience of the calculation, the triangle function is selected to design the preview fuzzy generator, and the formula is as follows:

$$f(x,a,b,c)=\begin{cases}0, & x\le a\\ \dfrac{x-a}{b-a}, & a\le x\le b\\ \dfrac{c-x}{c-b}, & b\le x\le c\\ 0, & x\ge c\end{cases} \tag{2}$$

In the formula, *x* is used for the specified variable of the universe of discourse, the shape of the triangle is specified by *a, b, c*, and $a\le b\le c$, and the maximum value *1* of the function is at point *b*, 0 for point *a, c*.

In the Matlab simulation, we used the Fuzzy toolbox to establish the membership function curve of the fuzzy variables *v(t)*, *k(t)*, *y(t),* as shown in Figure 5.

D. Fuzzy Deduction

a. Establishment of the fuzzy deduction rule table

The fuzzy deduction rule is the core of the fuzzy decision, which directly influences the performance result of the decision. The common methods to obtain the fuzzy deduction rule are to ask an experienced driver or to obtain experimental data. The preview fuzzy generator rule in the design is based on asking for navigational information from an experienced driver, as shown in Table 1.

b. Composing the algorithm for the input of the fuzzy collection

The preview fuzzy generator is a fuzzy logic system with double input. If the condition specified a rule, the composing calculation is often necessary for the different premises of input, to decide the front distance fuzzy value on the basis of the comprehensive fuzzy value input of the vehicle speed and the mean curvature of the path section. The common conjunction of the composing algorithm is "and" and "or". If the vehicle speed is very low (VL) and the path section mean curvature is very low (VS), then the front distance is very near (VN).

For simplicity of the calculation, the minimum method is used for the "and" operation, and the maximum method is used for the "or" operation, when the preview fuzzy generator is designed in the paper[21-23].

(1) Calculation of the "min" method

If the premise is "x is A and y is B", $A\times B$ is recorded as the fuzzy collection of the direct product space $X\times Y$, and then:

$$\mu_{A\times B}(x,y)=\min\{\ \mu_A(x),\mu_B(y)\ \} \tag{3}$$

(2) Calculation of the "max" method

If the premise is "x is A or y is B", $A\times B$ is recorded as the fuzzy collection of direct product space $X\times Y$, and then:

$$\mu_{A\times B}(x,y)=\max\{\ \mu_A(x),\mu_B(y)\ \} \tag{4}$$

c. Fuzzy deduction

For the following rules:

R: if x is A then y *is* B

The fuzzy relation R_c is defined as follows:

$$R_c = A\times B=\int_{X\times Y}\frac{\mu_A(x)\wedge\mu_B(y)}{(x,y)} \tag{5}$$

When x *is* A' and the composing algorithm of the fuzzy relation is "MAX—MIN", the concluding calculation of the fuzzy deduction is as follow:

$$B' = A'\circ R_c\int_Y\frac{\vee_{x\in X}(\mu_{A'}(x)\wedge(\mu_A(x)\wedge\mu_B(y)))}{y} \tag{6}$$

d. Composition of the output

The common conjunction "also" is used for the many diversified fuzzy rules. The "max" method is used to compose the multi-rules output when the preview fuzzy generator is designed in the research, and the calculation method is as follows:

$$\mu_{C_1\times C_2}(y_1,y_2)=\max\{\ \mu_{C_1}(y_1),\mu_{C_2}(y_2)\ \} \tag{7}$$

E. Defuzzy

The barycenter method is one of the Defuzzy methods that are more sensitive to the variation of a tiny fuzzy input value. Its output is obviously smoother than the other methods. The barycenter method is used to defuzzy when the preview fuzzy generator is designed; in this research, the method for calculating is as follows:

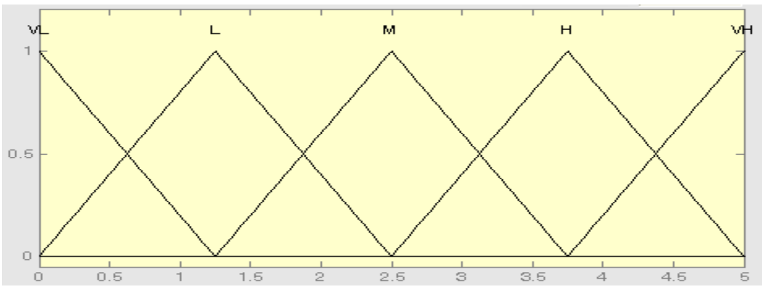
$$u_0=\frac{\int_U u\mu_0(u)du}{\int_U\mu_0(u)du} \tag{8}$$

In the formula, μ_0 is the fuzzy collection of variable u of the universe of discourse U.

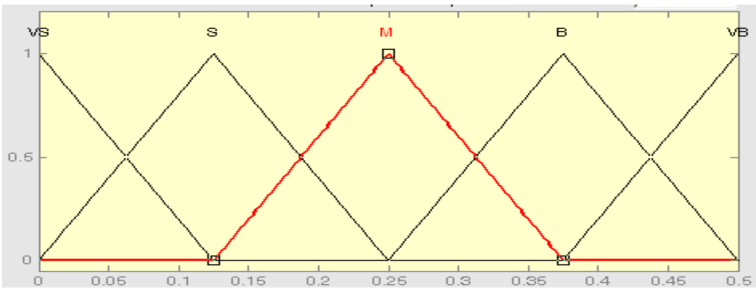
TABLE 1.

REASONING LANGUAGE RULE OF THE PREVIEW POINT FUZZY GENERATOR

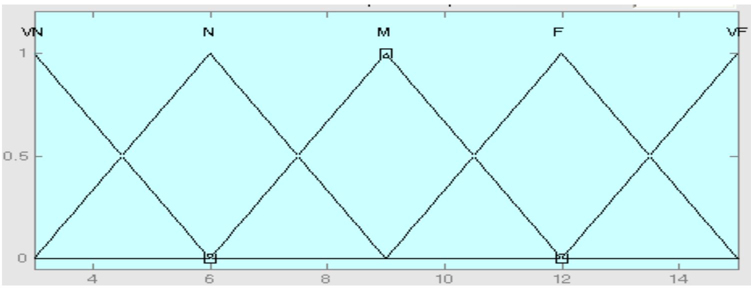
Vehicle speed	Curvature				
	VS	S	M	B	VB
VL	VN	VN	N	M	F
L	VN	N	N	M	F
M	N	N	M	F	F
H	M	M	F	F	VF
VH	M	F	F	VF	VF



(a)Membership function of the vehicle speed



(b) Membership function of the path section mean curvature



(c) Membership function of the front distance

Figure 5. Membership function of the fuzzy variable

III. Realization of the Algorithm

There are many ways to realize the preview fuzzy generator software, and table lookup is a simple and effective method that can guarantee very high real time performance for the system. Table lookup is used to realize the preview fuzzy generating algorithm. At first, the offline algorithm is used to generate the response table of the fuzzy decision, and in the actual control of the navigational preview control, the fuzzy decision output value is obtained directly by the table lookup based on the input value in the computer.

The response table of the fuzzy decision of the preview point fuzzy generator is calculated under Matlab, as shown in Table 2, and Figure 6 is the process chart of the preview point fuzzy calculation.

TABLE 2.

RESPONSE TABLE OF THE PREVIEW POINT FUZZY DECISION

Vehicle speed	Curvature										
	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
0	3.96	4.08	4.00	4.92	5.75	6.00	7.26	8.28	9.72	10.70	12.00
0.5	4.08	5.27	5.47	5.47	5.85	6.00	7.20	8.39	9.61	10.80	12.00
1.0	4.00	5.47	5.95	5.95	5.98	6.00	7.23	8.34	9.66	10.80	12.00
1.5	4.92	5.47	5.95	6.20	6.61	6.72	7.66	9.00	9.66	10.80	12.00
2.0	5.75	5.85	5.98	6.61	7.80	7.74	9.00	10.30	10.80	11.1	12.00
2.5	6.00	6.00	6.00	6.72	7.74	9.00	10.30	11.30	12.00	12.00	12.00
3.0	7.26	7.20	7.23	7.66	9.00	10.30	10.20	11.40	12.00	12.20	12.30
3.5	8.28	8.39	8.34	9.00	10.30	11.30	11.40	11.80	12.10	12.50	13.10
4.0	9.00	9.43	9.66	9.66	10.80	12.00	12.00	12.10	12.10	12.50	14.00
4.5	9.00	10.20	10.80	10.80	11.10	12.00	12.20	12.50	12.50	12.70	13.90
5.0	9.00	10.30	11.30	12.00	12.00	12.00	12.30	13.10	14.00	13.90	14.00

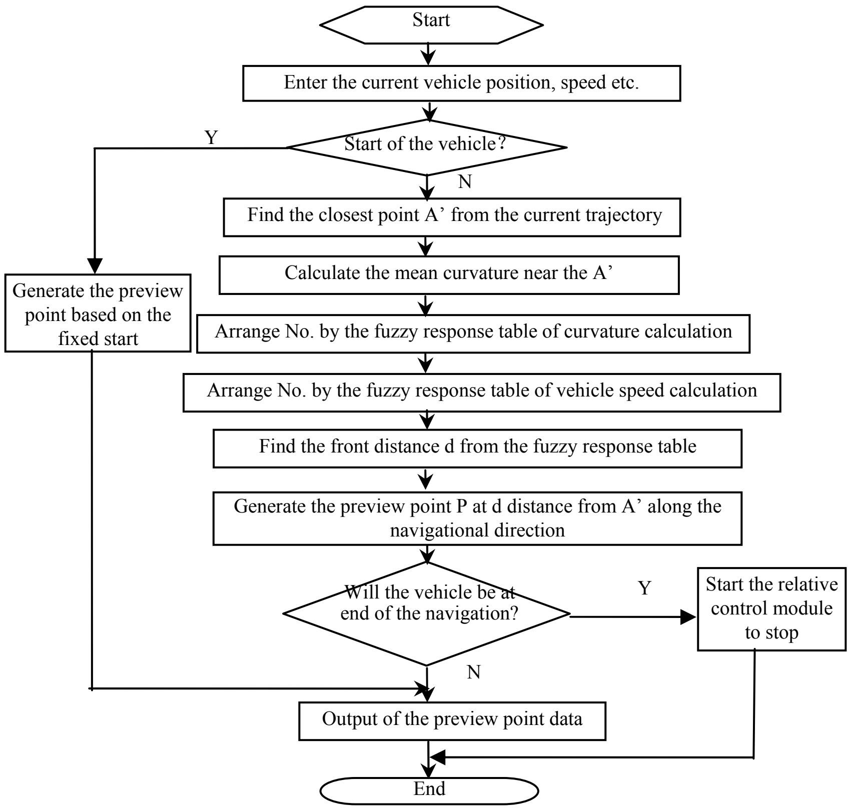


Figure 6. Process chart of the preview point fuzzy calculation

V. Experimental Verification

According to the actual requirement of the field operation, the vehicle speed is controlled at approximately 0.8 m/s, tested on the straight, the 90° curve and the arc path, separately. The yaw is taken by a 1 m step according to the actual trace of the vehicle trace navigation on the test ground and converted into the space coordinate points on the map, while keeping the yaw at the point. Table 3 is the trace data analysis of 3 predetermined trajectories, and Figure 7 is the line graph of the trace error.

From table 3, it could be concluded that the lateral DRMS (distance root mean square error) of the straight trace of the rice transplanting robot is approximately 0.33 m, and the maximum error is approximately 0.71 m; the lateral DRMS of the 90°curve trace is approximately 0.73 m, and the maximum error is approximately 1.85 m; the lateral DRMS of the arc way trace is approximately 1.03 m, and the maximum error is approximately 2.56 m; and the total mean error is approximately 0.6 m.

TABLE 3.
TRACE DATA ANALYSIS OF THE PREDETERMINED NAVIGATION

Path section	Samples	Maximum error (m)	Extreme difference (m)	Mean error (m)	DRMS (m)
Straight way	61	0.708	0.698	0.282	0.334
90°curve	109	1.849	1.849	0.600	0.732
Arc way	119	2.563	2.511	0.939	1.032
			Total mean	0.607	

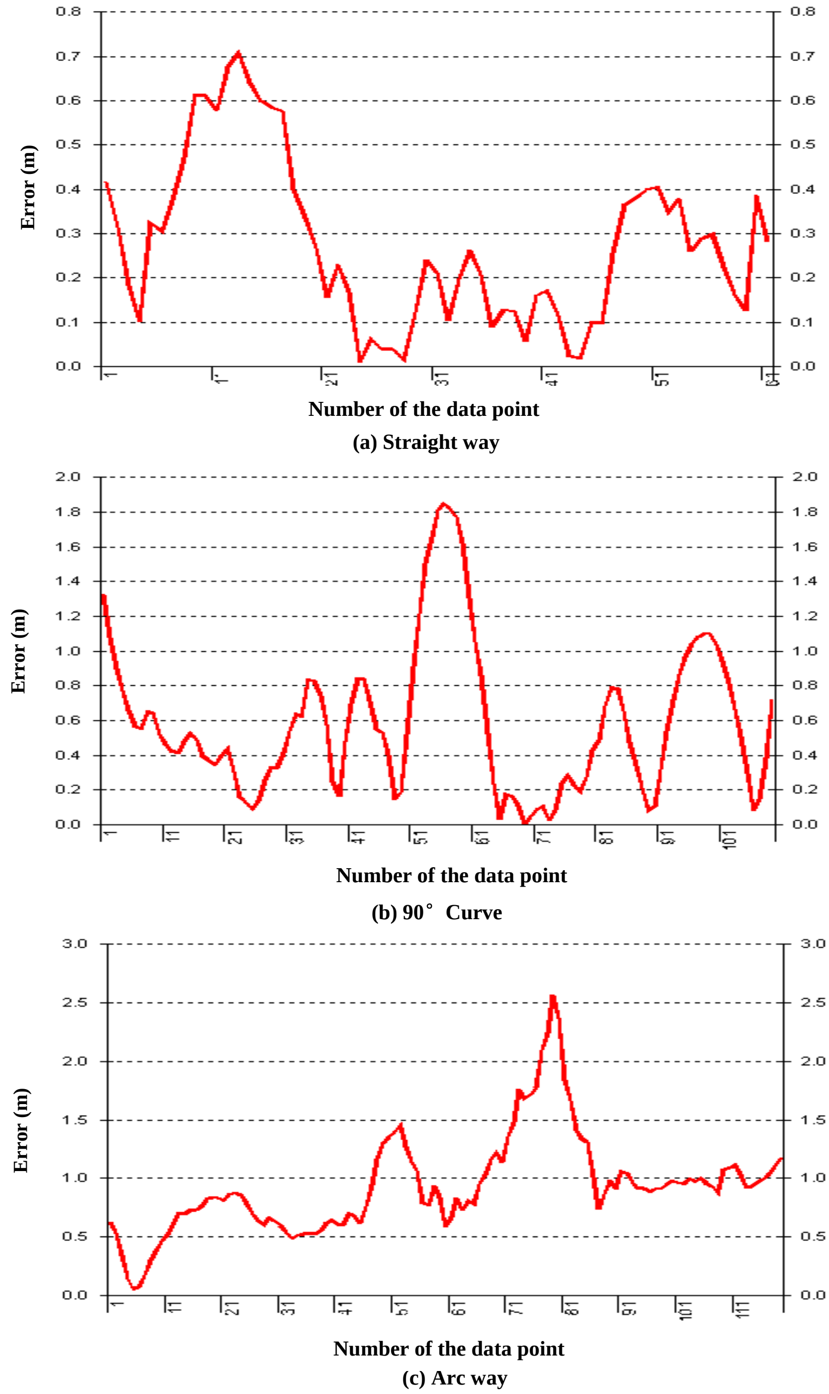


Figure 7. Error variation trend while tracing the predetermined trajectory

VI. Conclusions

Based on the “preview follower theory” combined with the driver’s experience and use of the Matlab fuzzy control toolbox, a fuzzy algorithm of the preview point was designed. To realize the dynamic auto-regulation of path preview control and improve the trace precision of the path, a navigational control system embedded in a path planning and preview control algorithm was applied in the experiment to operate a rice transplanting robot by tracing the predetermined navigation of a straight way, 90°curve and arc way. The results indicated that the lateral DRMS of the straight trace is approximately 0.33 m, and the maximum error is approximately 0.71 m; the lateral DRMS of the 90°curve trace is approximately 0.73 m, and the maximum error is approximately 1.85 m; the lateral DRMS of the arc way trace is approximately 1.03 m, and the maximum error is approximately 2.56 m; and the total mean error is approximately 0.6 m. Based on the outcome of the experiment, the relevant algorithm can largely meet the requirements for rice transplanting robot guidance.

REFERENCES

[1] Z. Zhou, Study on the Navigation Geographic Information System for the Intelligent Farming Chassis, Dissertation: South China Agricultural University, Guangzhou, 2005

[2] Y. Nagasaka, H. Saito, K. Tamaki, M. Seki, K. Kobayashi and K. Taniwaki, "An autonomous rice transplanter guided by global positioning system and inertial measurement unit", *Journal of Field Robotics*, vol.26, no.6-7, pp.537-548, 2009

[3] C. Cariou, R. Lenain, B. Thuilot and M. Berducat, "Automatic guidance of a four-wheel-steering mobile robot for accurate field operations", *Journal of Fied Robotics*, vol.26, no.6-7, pp.504-518, 2009

[4] Y. Nagasaka, H. Kitagawa, A. Mizushima, N. Noguchi, H. Saito and K. Kobayashi, "Unmanned rice-transplanting operation using a gps-guided rice transplanter with long mat-type hydroponic seedlings", *Agricultural Engineering International: CIGR Journal*, vol.IX, pp.1-10, 2007

[5] R. Lenain, B. Thuilot, C. Cariou and P. Martinet, "High accuracy path tracking for vehicles in presence of sliding: application to farm vehicle automatic guidance for agricultural tasks", *Autonomous Robots*, vol.21, no.1, pp.79-97, 2006

[6] X. Luo, Z. Zhang, Z. Zhao, B. Chen, L. Hu and X. Wu, Design of DGPS navigation control system for Dongfanghong X-804 tractor. *Transactions of Chinese Society of Agricultural Engineering*, vol.25, no.11, pp.139-145, 2009

[7] J. Gomez-Gil, J. C. Ryu, S. Alonso-Garcia and S. K. Agrawal, "Development and validation of globally asymptotically stable control laws for automatic tractor guidance", *Applied Engineering in Agriculture*, vol.27, no.6, pp.1099-1108, 2011

[8] I. A. Hameed, C. G. Sorrenson, D. Bochtis and O. Green, "Field robotics in sports: automatic generation of guidance lines for automatic grass cutting, striping and pitch marking of football playing fields", *International Journal of Advanced Robotic Systems*, vol.8, no.1, pp.113-121, 2011

[9] H. Peng and M. Tomizuka, "Preview control for vehicle lateral guidance in highway automation", *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, vol.115, no.4, pp.679-686, 1993

[10] J. Cai and L. Li, "Autonomous navigation strategy in mobile robot", *Journal of computers*, vol.8, no.8, pp.2118-2125, 2013

[11] D. Gong, J. Zhang and Y. Zhang, "Multi-objective particle swarm optimization for robot path planning in environment with danger sources", *Journal of Computers*, vol.6, no.8, pp.1554-1561, 2011

[12] Z. Jiang and T. Ishita, "A neural network controller for trajectory control of industrial robot manipulators", *Journal of Computers*, vol.3, no.8, pp.1-8, 2008

[13] J. Park and P. E. Nikravesh, "A look-ahead driver model for autonomous cruising on highways", *Sensors, safety systems, and human factors*,1996

[14] T. Bell. "Precision robotic control of agricultural vehicles on realistic farm trajectories". 1999. stanford university,

[15] Q. Zhang and H. Qiu, "A dynamic path search algorithm for tractor automatic navigation", *Transactions of the Asae*, vol.47, no.2, pp.639-646, 2004

[16] Z. Gao, X. Guan and K. Guo, Application of preview follower theory and driver modeling the research of vehicle intelligent handling. *Journal of Traffic and Transportation Engineering*, no.2, pp.63-66, 2002

[17] Q. Li, W. Gu, X. Ye and Z. Xiang, A study of intellegent preview control method for mobile robot road following. *Robot*, no.3, pp.252-255, 2002

[18] K. Guo, Preview follower theory and simulations of large angle cornering motion of a man-vehicle system. *Automotive Engineering*, vol.14, no.1, pp.1-11, 1992

[19] Z. Gao, X. Guan, Q. Li and K. Guo, Driver Follower Control Model with Vehicle Target Velocity Based on Preview Follower Theory. *Journal of Jilin University of Technology*, vol.32, no.1, pp.1-5, 2002

[20] H. LI and Y. LI, Matlab and C mixed programming to implement type-2 fuzzy logic system. *Computer Engineering and Design*, vol.28, no.14, pp.3291-3294, 2007

[21] J. Kluska and K. Wiktorowicz, "Automatic generating of fuzzy control rules for a fuzzy logic controller using matlab", *Systems Science*, vol.23, no.1, pp.89-99, 1997

[22] Z. Wu, Q. Zhu, A. Winfield and S. Chen, "Study of fuzzy control for controllable suspension based on adams and matlab co-simulation", *International Journal of Modelling, Identification and Control*, vol.9, no.1-2, pp.190-198, 2010

[23] A. Pinti, F. Rambaud, J. Griffon and A. T. Ahmed, "A tool developed in matlab for multiple correspondence analysis of fuzzy coded data sets: application to morphometric skull data", *Computer Methods and Programs in Biomedicine*, vol.98, no.1, pp.66-75, 2010

Dr. Zhiyan Zhou received a PhD degree in Agricultural Electrification and Automation from South China Agricultural University in 2011. He is an Associate Professor at South China Agricultural University. His interests are in intelligent equipment for precision agriculture.

Dr. Zhigang Zhang received a PhD degree in Agricultural Electrification and Automation from South China Agricultural University in 2006. He is an Associate Professor at South China Agricultural University Currently. His interests are in intelligent equipment for precision agriculture.

Prof. Xiwen Luo received a Master's degree in Agricultural Machinery Engineering from South China Agricultural University in 1992. He worked as a visiting scholar at Virginia Polytechnic Institute and State University and the University of Kentucky from 1987 to 1989. He is an Academician at the Chinese Academy of Engineering and a Professor at South China Agricultural University. His research interests include agricultural engineering.