MODELING AND ANALYSIS OF AN AGRICULTURAL VEHICLE CROSS-BOUNDARY WARNING SYSTEM
/
农业车辆田间作业越界预警系统建模与分析

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ABSTRACT
In order to improve the safety of agricultural vehicle in the field, we established a vehicle kinematics model for hanging agricultural tools, and comprehensively considered driving speed, the agricultural tool rotation radius, and vehicle movement trend to propose an agricultural vehicle field operation cross- boundary warning method based on a Robot Operating System (ROS). Furthermore, we designed a set of agricultural vehicle safety warning systems and employed Qt Creator to develop the agricultural vehicle warning system operation interface. Following this, a test platform was built based on the Oubao 4040 tractor and unilateral cross-boundary warning tests were conducted. Test results demonstrate the ability of the proposed cross-boundary warning system to: i) correctly determine the warning area at different speeds (low (3.6km/h±0.5km/h), medium (10.8km/h±1.0km/h) and high (18.0km/h±1.5km/h)) and driving paths ("V" and "U"-shaped routes); ii) and to prompt the operator in a timely manner. The proposed framework exhibits strong applicability and improves the safety of agricultural vehicle hanging agricultural tools.

摘要
为提高农业机械田间作业的安全性，本研究建立了悬挂农具的车辆运动学模型，综合考虑了行驶速度、农具旋转半径与车辆运动趋势，提出了一种农业机械田间作业越界预警方法，并基于 ROS 系统设计了一套农业机械安全预警系统，使用 Qt Creator 开发了农业机械预警系统操作界面，搭建了以欧豹 4040 型拖拉机为基础的试验平台，进行了单边越界预警试验。试验结果表明，本研究设计的越界预警系统在不同速度（低速（3.6km/h±0.5km/h），中速 （10.8km/h±1.0km/h）和高速（18.0km/h±1.5km/h））与不同行驶路径（"V"和"U"型路线）下均能正确判断预警区，并能够及时提示操作人员，具有良好的适用性，具有提高悬挂农具的农业车辆田间作业安全性的潜力。

INTRODUCTION
The agricultural sector field is currently experiencing a rapid development in the field of intelligence, particularly the navigation technology of agricultural vehicles. The safety of agricultural vehicles in the field has always been the concern of researchers and farmers (*Khorsandi F, et al., 2019; Latorre-Biel J A, et al., 2019*). *Weichelt and Gorucu* (2018) report that All-Terrain Vehicle (ATV) accidents were the second most common injury source in US agriculture, causing 190 injuries or deaths (63% fatal). Safety warnings are crucial for the safe and reliable independent running of agricultural vehicles (*Mousazadeh H, 2013*). Agricultural vehicle safety warnings typically includes vehicle rollover warnings, wheel slip warnings, obstacle warnings and cross boundary warnings (*Hickman J S et al., 2015; Tian Y, 2018; Vidoni R, et al, 2015; Zhu B, et al., 2016; Zhao T, et al. 2016; Zhu T, et al, 2011*). The theory of cross-boundary warning has continuously developed over the recent years, resulting in an increase in its applications. However, despite the recent progress, research cross-boundary warnings based on satellite positioning in agricultural vehicle navigation is relatively limited (*Guo et al., 2019*).

Traditional methods generally regard the farmland road marking line and crop boundary as the operation boundary of agricultural vehicles. Farmland imagery, which is typically obtained by one or two cameras, is used to extract farmland road signs and navigation lines via segmentation, clustering, and the Hough transformation (*Bonadies S and Gadsden S A, 2019; Li X, et al., 2020; Song Y, et al., 2017; Zeng H, et al., 2020; Zhao T, et al. 2016*). These extracted features are combined with deep learning methods to prevent agricultural vehicles from crossing the boundary.

Traditional cross-boundary warning technology is largely dependent on the sensor's perception of the surrounding environment, yet complex farmland environments increase the amount of computing resources consumed by the sensing algorithms (*Zhang M, et al., 2020*).

The development of Global Navigation Satellite Systems (GNSS) has increased the applications of electronic fence technology in security, railway, aviation, etc. (*Figueiras J, et al., 2012; Cheng H, et al., 2017; Hsu C, et al., 2019; Hu J, et al, 2018; Monod M O, et al., 2008; Yuan Z, et al., 2017*). In particular, electronic fence technology is able to employ satellite positioning coordinates to set the working area, install GNSS signal receiving equipment on the working device to locate position, and determine whether the working device is in the working area via its coordinates. *Yang et al. (2016)* employed an electronic fence to set the plant protection operation area of unmanned aerial vehicles (UAVs) and was able to find out whether the UAV crossed the boundary in real time via a ray detection algorithm. Results demonstrated the ability of electronic fence technology to reliably monitor UAV plant protection operations. *Zhao (2019)* designed an earthing warning system for tractors based on the Beidou System (BDS), but failed to employ electronic fences to the cross-boundary warning of agricultural vehicles.

In the current study, in order to improve the safety of agricultural vehicle field operations, we employ electronic fence technology to limit the operational range of agricultural vehicles. A field operational cross-boundary warning framework for agricultural vehicles based on satellite positioning is proposed by integrating the speed of agricultural vehicles, the rotation radius of agricultural tools, the movement trend of vehicles, and the vehicle kinematics model of hanging agricultural tools. The front wheel angle encoder and BDS are installed on an Oubao 4040 tractor and the agricultural vehicle safety warning system is designed based on a Robot Operating System (ROS).

MATERIALS AND METHODS

Mathematical modeling of vehicle kinematics and the warning system

We selected the agricultural tractor as the research object and established a kinematic model for the tractor (Fig. 1). Note that we did not consider the influence of factors such as slip, side deviation and ground flatness during the tractor driving process. The model is expressed as equation 1, while equation 2 represents the relationship between turning radius R_2 of the agricultural tools and turning radius R_1 of the tractor.

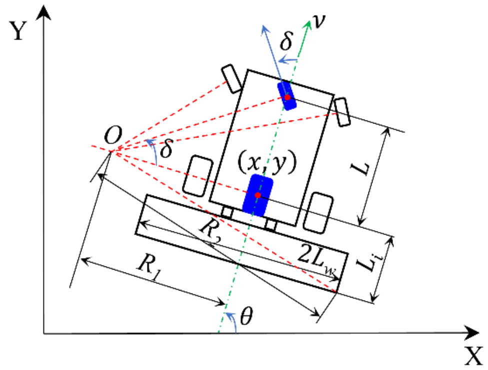

Fig. 1 - Proposed kinematics model of tractor-mounted farm tools

$$\begin{aligned} \dot{x} &= v\cos\theta \\ \dot{y} &= v\sin\theta \\ \dot{\theta} &= \omega = \frac{v}{L}\tan\delta \end{aligned} \quad (1)$$

$$\begin{aligned} R_1 &= L / \tan\delta \\ R_2 &= \sqrt{(R_1 + L_w)^2 + L_i^2} \end{aligned} \quad (2)$$

where: x and y – the global coordinates of the tractor rear axle centre (m);

θ – The heading angle of the tractor in the global coordinate system (°);

ω – The angular speed of the tractor (rad/s);

v – The driving velocity of the tractor, $v \in (0, v_{max}]$ (m/s);

δ – The steering angle of the tractor's front wheels (°);

L – The distance between the front and rear wheels of the tractor (m);

L_i – The distance between the farm tool and the rear wheel axis of the tractor (m);

L_w – Half of the total width of the farm tools (m);

R_1 – The turning radius of the tractor (m);

R_2 – The rotation radius of the tractor-mounted farm tools (m).

The operation boundary of the agricultural vehicles refers to the boundary of the electronic geofence preset by the operator via the latitude and longitude and is based on the size of the farmland. Agricultural vehicles perform field operations within an electronic geofence and cannot go beyond the geofence. When the agricultural vehicles approaches the boundary, a warning is required in order to alert the operators.

Fig. 2 presents the proposed cross-boundary warning model. Straight line MN denotes the operation boundary in terms of the latitude and longitude. $Q(x_k, y_k)$ are the GNSS-determined tractor coordinates at time k, and point $Q'(x_{k+1}, y_{k+1})$ represents the position of the tractor following time ΔT, which is predicted by the kinematic model via equation 4.

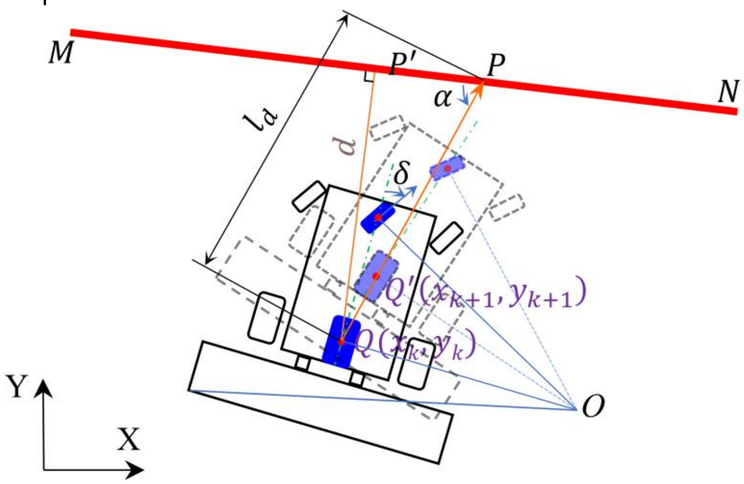

Fig. 2 - Schematic diagram of cross-boundary warning model

$$\begin{aligned} A_1x + B_1y + C_1 = 0 \\ A_2x + B_2y + C_2 = 0 \end{aligned} \tag{3}$$

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \end{bmatrix} + v_k \Delta T \begin{bmatrix} \cos\delta_k \\ \sin\delta_k \end{bmatrix} \tag{4}$$

$$\lambda = \frac{\sqrt{|A_1x_k + B_1y_k + C_1|}}{\sqrt{|A_1x_{k+1} + B_1y_{k+1} + C_1|}} \tag{5}$$

$$\alpha = \arccos\frac{A_1A_2 + B_1B_2}{\sqrt{A_1^2 + B_1^2}\sqrt{A_2^2 + B_2^2}}, \alpha \in [0, \pi/2] \tag{6}$$

$$d = \frac{|A_1x_k + B_1x_k + C_1|}{\sqrt{A_1^2 + B_1^2}} \tag{7}$$

$$l_d = \frac{d}{\sin\alpha} \tag{8}$$

where:

A_1, B_1 and C_1 – The parameters of operation boundary line *MN*;

A_2, B_2 and C_2 – The parameters of ray *QQ′*;

λ – the cross-boundary trend parameter, where $\lambda>1$, and $\lambda<1$ indicate a tendency of the vehicle to drive to and leave the specified boundary, respectively, and $\lambda=1$ indicates a direction of travel that is parallel to the specified boundary or at rest;

d – The vertical distance between the vehicle coordinate point and boundary line (m);

α – The angle between ray *QQ′* and operation boundary line *MN* (°).

Agricultural vehicles operate parallel and close to the boundary line, which consequently introduces a cross-boundary risk that must be assessed by the cross-boundary warning model in order to warn the operator. Therefore, parameter ξ was introduced to broaden the range used to determine whether the vehicle was stationary or parallel. The distance between the vehicle and the boundary was then determined via equation 9.

$$\begin{cases} dist = l_d, \lambda > 1+\xi \\ dist = d, 1-\xi \le \lambda \le 1+\xi \\ dist = \infty, \lambda < 1-\xi \end{cases} \quad (9)$$

The cross-boundary warning was divided into three levels: i) green indicates that it is safe to drive at this time; ii) yellow specifies that the tractor is gradually approaching the boundary of the driving direction and warns the operator to leave the warning state via steering; and iii) red warns the operator that the steering operation is no longer able to take the vehicle out of the warning state at this time, and the vehicle must leave the warning state. We determined the warning distance by taking into account the minimum turning radius of the vehicle as follows:

$$l_t = \mu(Av^2 + Bv) + \tau C \quad (10)$$

where: A=1/2 a_{max}, a_{max} – the maximum braking acceleration of agricultural vehicles, 7 m/s;
B – The operator response time, 0.7 *s*;
μ – The vehicle speed safety factor, μ >1;
C – The minimum turning radius of the tractor-mounted agricultural tools, R_{2min}, m;
τ – The safety factor of vehicle turning, τ >1.

In the first quadrant of the v-l coordinate system, the quadratic curve $l_t=\mu(Av^2+Bv)+\lambda C$, the straight lines $v=v_{max}$, and $l_c=\lambda C$ divide the coordinate system into the green, yellow and red regions. The warning level was evaluated by comparing the actual distance between $dist$, l_t and l_c during the driving process (Fig. 3). For $v=v_1$, $dist=l_1\in[0, l_c]$, $dist=l_2\in(l_c, l_t]$ and $dist=l_3\in(l_t,+\infty)$ denote red, yellow and green.

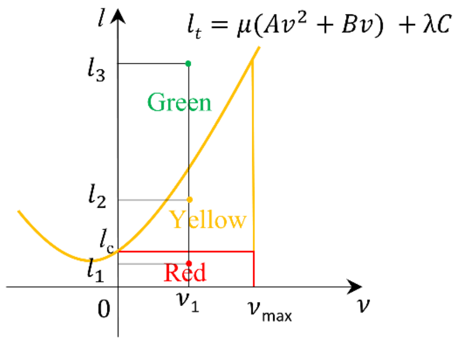

Fig. 3 - Schematic diagram of the cross-boundary warning level classification

Hardware and software

In order to test the proposed cross-boundary warning model, we established a test platform using a Oubao 4040 tractor with front-wheel steering and rear-wheel driving (Fig. 4).

Tab. 1 reports the key parameters of the test platform.

Table 1

Key performance parameters of the test platform

Type	Length, width and height (mm)	Front wheel track (mm)	Rear wheel track (mm)	Engine power (kW)	Speed range (km/h)
Oubao 4040	3200×1800×2110	1320	1300	29.40	2.65～34.78

We employed Raspberry Pi 4B and Ubuntu 18.04LTS as the controller and operating system, respectively, as well as XW-GI5610 (sampling frequency: 10Hz; manufactured by StarNeto Co., Ltd., China) as the positioning equipment. The mobile station GNSS antenna was fixed on the top of the test platform in order to set the base station XW-GPS1060 coordinate information.

The base station and the mobile station were integrated with GE MDS EL-7052 series data transmission radio communication system to form an RTK-GNSS (real time kinematic-global navigation satellite system), allowing for centimetre-level positioning accuracy.

The test platform was centred around a ROS-based software system. More specifically, ROS Melodic was installed under the Ubuntu 18.04 LTS operating system to obtain GNSS positioning data through the serial port. In order to detect the front wheel angle, the Wittower absolute rotary encoder (±45° detection range, 11 bit detection accuracy and 12 bit resolutions) was placed on the steering column of the front left wheel. Based om the calibration results, the ROS node Arduino was used to collect and convert the encoder output voltage into the front wheel angle. Arduino then published the front wheel angle through the serial port to the ROS at a frequency of 50 Hz.

Fig. 4 - Cross-boundary warning test platform

Fig. 5 presents the proposed agricultural vehicle warning system operation interface developed by Qt Creator. The interface was divided into two components: the agricultural vehicle obstacle warning and agricultural vehicle cross-boundary warning. In the current study, we focused on the latter, reserving the former for future research. The frequency of warning information released by the agricultural vehicle cross-boundary warning was consistent with the sampling frequency of GNSS (10Hz).

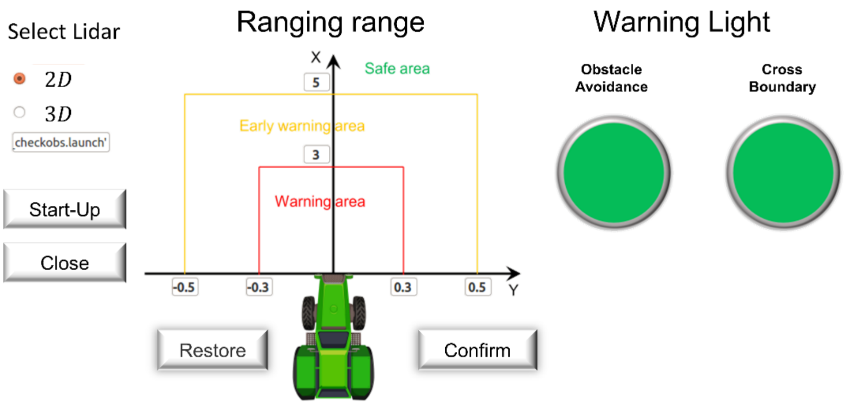

Fig. 5 - Operational interface of the agricultural vehicle warning system

Experiment methods

- **Calibration test of the tractor front wheel angle**

Once the encoder was installed on the front wheel column, the line drawing method was applied to calibrate the front wheel angle and the encoder output value. In particular, the front wheel turned left to positive and right to negative. The front axle of the tractor was then held via a jack, raising the front wheels off the ground to place the A0 drawings below them. Following this, the steering wheel was turned such that the front wheels faced parallel to the body. The front wheel angle was recorded as 0° and the encoder was returned to 0. The steering wheel was then turned from left to right to determine whether the encoder output voltage exceeded the range. When the range was not exceeded in both directions, calibration was subsequently performed (Fig. 6).

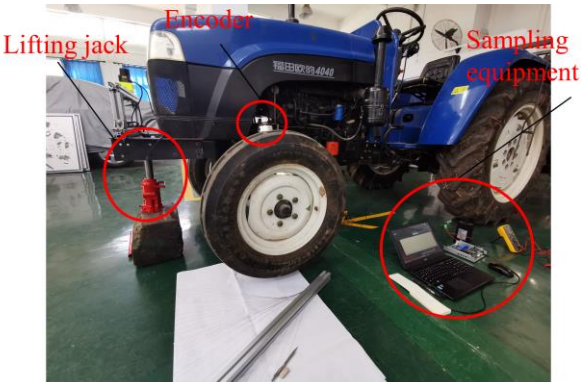

Fig. 6 - Calibration of the tractor front wheel angle via the line drawing method

- **Agricultural vehicle boundary warning experiment**

The single-boundary cross-boundary warning test simulated the process of the agricultural vehicle in the field, warning the agricultural vehicle of cross-boundary behaviour, and detecting the warning level of the cross-boundary warning model.

A GNSS device initially set two boundary points, which were then connected to form a working boundary. Low (3.6km/h±0.5km/h), medium (10.8km/h±1.0km/h) and high (18.0km/h±1.5km/h) speeds were used for the agricultural vehicle when driving to the operating boundary via "V" and "U"-shaped routes (Fig. 7). We monitored the state of the cross-boundary warning lights and the actual cross-boundary status of the agricultural vehicle in order to determine the accuracy of the warning. The agricultural vehicle traversed the "V" and "U" routes and record the state of the cross-boundary warning lights. We assumed that the tractor hung a farm tool with a width and installation distance of 4 m and 1 m, respectively. We chose point *M* (506313.000, 3795910.000) and *N* (506313.000, 3795960.000), *MN* as boundary line. According to the previous test, we set ξ=0.01, μ=2 and τ=1.5. The experiment was performed on the lawn on the west side of the School of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, China (Fig. 8).

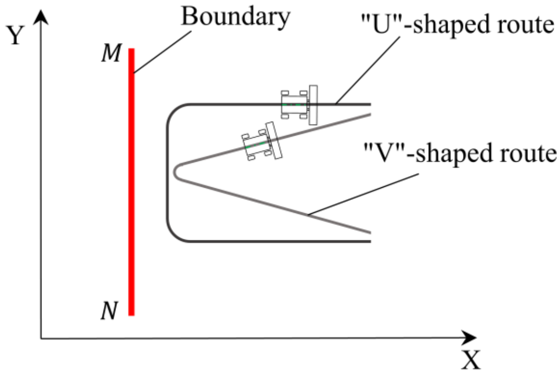

Fig. 7 - Route map of test vehicle

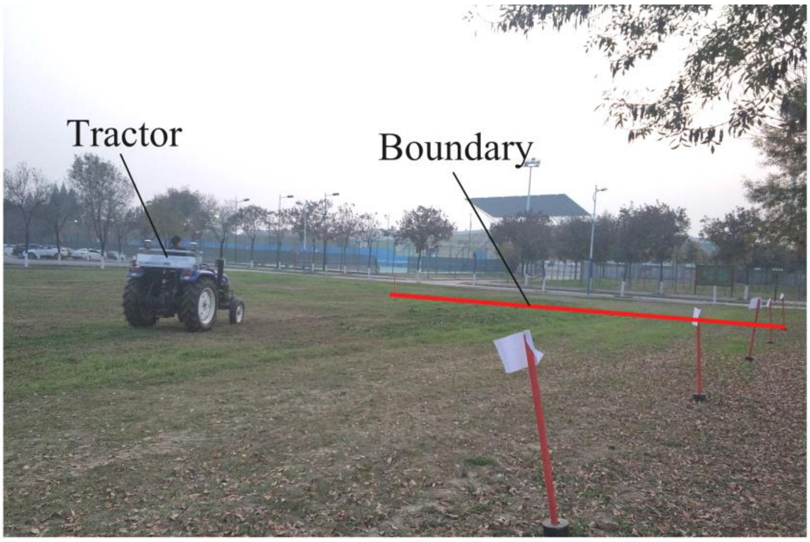

Fig. 8 - Cross-boundary warning field test

The implementation steps of the algorithm are as follows: i) obtain the operation boundary based on GNSS coordinates; ii) obtain the position, speed and front wheel angle data of agricultural machinery; iii) calculate *dist* according to the algorithm proposed in this study, compare *dist*, l_t and l_c, and send out warning signal.

RESULTS AND DISCUSSION

A total of 33 datasets were recorded during the front wheel angle calibration test, and calibrated using Origin (2018, OriginLab) (Fig. 9). The results were fit with a straight line with R^2 = 0.99975, demonstrating the strong linearity between the front wheel angle value and the encoder output value. Thus, the encoder output value can be employed to calculate the front wheel angle.

The proposed cross-boundary warning model of the agricultural vehicle was tested on the tractor testing platform. Raspberry Pi 4B was used for the data processing and display terminal. We performed the cross-boundary warning tests in order to comprehensively analyse the cross-boundary warning model. The point locations and warning level data were exported and visually analysed via Python. Fig. 10, Fig. 11 and Fig. 12 present the scatter plots of the exported data, where the colour of the point indicates the warning level. Fig. 10, 11 and 12 show that the system will correctly determine the warning area at different speeds (low (3.6 km / h ± 0.5 km / h), medium (10.8 km / h ± 1.0 km / h) and high (18.0 km / h ± 1.5 km / h)) and different driving paths ("V" and "U"-shaped routes). The yellow warning zone is (6.74m, 8.28m], (6.74m, 12.20m] and (6.74m, 17.24m] respectively for low, medium and high-speed, which indicates that the yellow warning zone is observed to be shorter for agricultural vehicles driving at lower speeds, and subsequently increases with speed. The expansion of the yellow warning zone aids operators in determining warning signs in order to take timely preventive measures. Compared with the cross-boundary warning algorithm proposed by Yang et al. (2016), the proposed algorithm reduces the steps of generating safe operation boundary, simplifies the complexity of the algorithm, and improves the response speed of the algorithm.

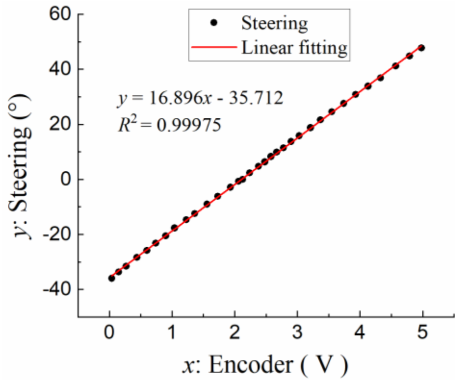

Fig. 9 - Calibration results of the front wheel angle

The red warning zone was determined via the minimum turning radius of the agricultural vehicles and the size of the suspended agricultural vehicle. As the driving speed increased, the collected location points became sparser. This is not conductive to the accurate determination of out-of-bounds warnings due to the dependence of the out-of-bounds warning system on positioning data.

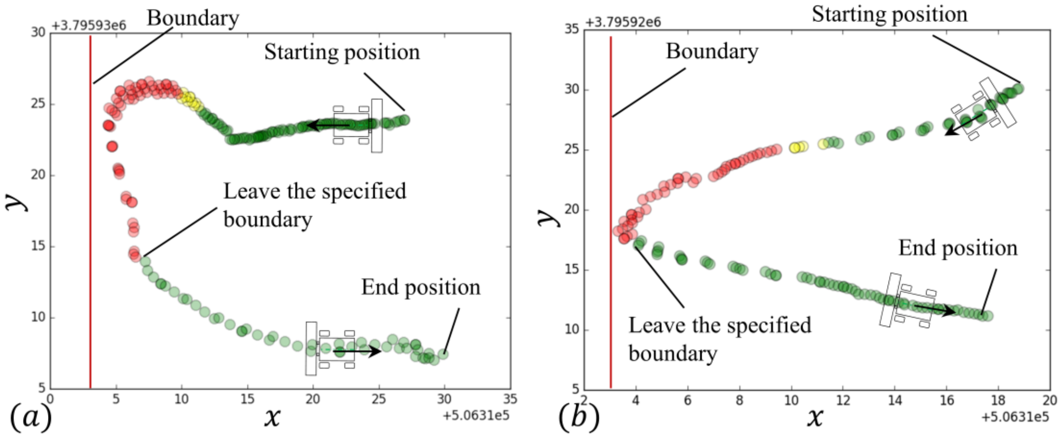

Fig. 10 - Agricultural vehicles driving at low speed for the (a) "U"-shaped route and (b) "V"-shaped route Red warning zone [0.00m, 6.74m], yellow warning zone (6.74m, 8.28m] and green zone (8.28m, + ∞)

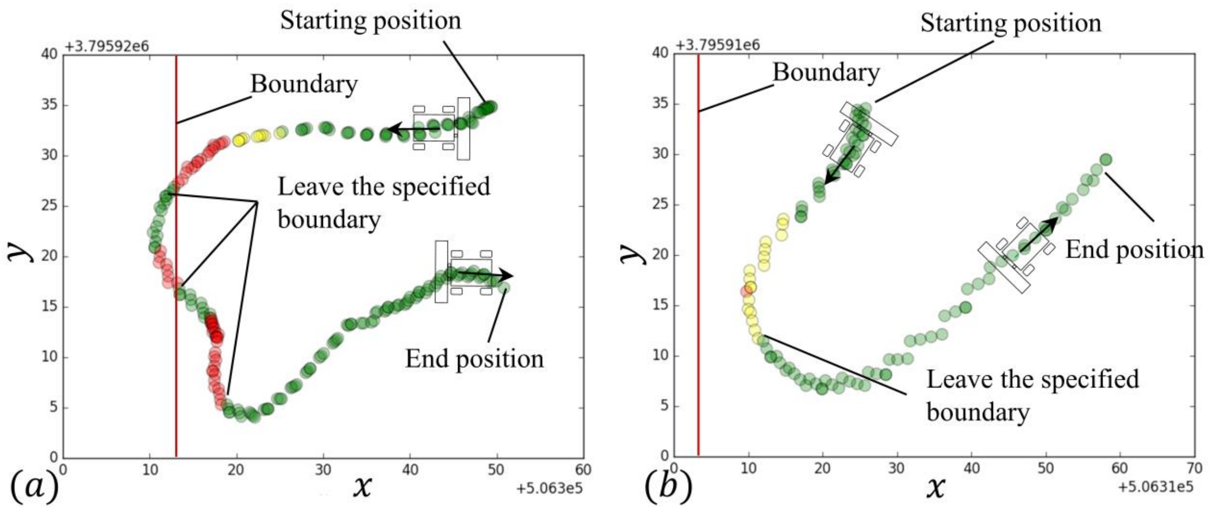

Fig. 11 - Agricultural vehicles driving at medium speed for the (a) "U"-shaped route and (b) "V"-shaped route Red warning zone [0.00m, 6.74m], yellow warning zone (6.74m, 12.20m] and green zone (12.20m, + ∞)

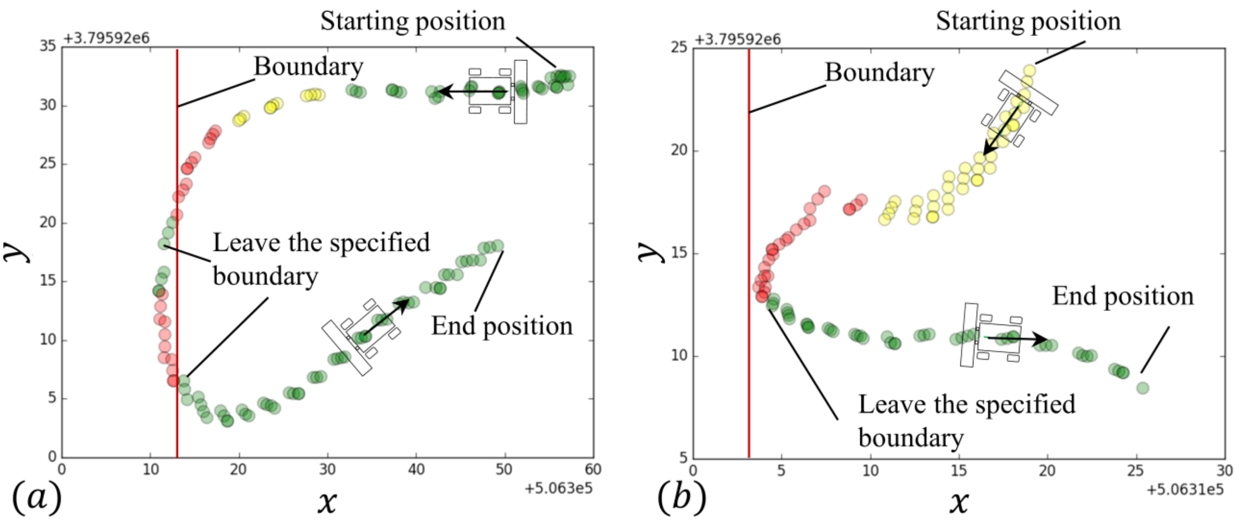

Fig. 12 - Agricultural vehicles driving at high speed for the (a) "U"-shaped route and (b) "V"-shaped route Red warning zone [0.00m, 6.74m], yellow warning zone (6.74m, 17.24m] and green zone (17.24m, + ∞)

Agricultural vehicles driving close to the boundary are located in the yellow and red warning zones. In contrast, for agricultural vehicles driving away from the boundary, the cross-boundary risk is limited and no warning is given. Thus, in the proposed warning model, driving away from the boundary is regarded as the safest situation. The results demonstrate that for agricultural vehicles driving close to the boundary, the system is able to output the correct warning. Figures 11 (a) and 12 (a) reveal that agricultural vehicles still use the previous crossing warning rules after crossing the boundary, which is not conducive to the field operation of agricultural vehicles. Therefore, it is necessary to judge whether the agricultural vehicle is inside the polygon boundary when we conduct the polygon boundary warning test.

CONCLUSIONS

(1) In the current study, we focused on the problem of cross-boundary risk for agricultural vehicles by comprehensively considering the driving speed, the rotation radius of farm tools and the movement trend of the vehicle. We proposed a warning framework for cross-boundary farming machinery based on the kinematics model of hanging farm tools.

(2) The proposed cross-boundary warning system can correctly determine the warning zone at different speeds and driving paths, demonstrating good applicability and reliability. For agricultural vehicles with a tendency to cross the boundary, the system will warn the operator, which improves the safety of agricultural vehicles in the field.

(3) The detection method of the agricultural vehicle cross-boundary warning system is simple, computationally inexpensive and has limited performance requirements. It can accurately determine whether the agricultural vehicle crosses the boundary in real time in order to prompt the operator in a timely manner, effectively improving the safety of agricultural vehicle operations. However, in the current study, only a single boundary was tested.

In order to further develop the proposed model, future research will test polygon boundaries to detect the effectiveness of cross-boundary warnings and equip emergency braking device on agricultural vehicles to avoid the operator neglecting the warning signal.

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