Path Planning and Trajectory Tracking Control of Large Intelligent Mowing Robot Based on GPS-RTK

Jiehua Zhou, Yongguo Zhu and Cihui Yang

***Abstract*—**In order to improve the mowing efficiency in large lawn, a large intelligent mowing robot was designed by using the technology of mobile robot and global positioning system-real time kinematic (GPS-RTK). The path planning and trajectory tracking control must be solved for realizing its application. Firstly, the paper introduces the functions of each subsystem and establishes the robot's kinematics model by using Ackerman model. Secondly, according to the GPS information, a round-trip straight path planning and trajectory tracking control algorithm were proposed in the polygon working area. Finally, the path planning and trajectory tracking control algorithms were simulated and experimental studied. The cutting leakage rates of simulation and experiment are respectively 7.15% and 8.89%. The results show that the proposed path planning and trajectory tracking control algorithms are effective.

***Keywords*—**intelligent mowing robot, path planning, trajectory tracking.

I. INTRODUCTION

UNDER the background of social progress and economic development, people's demand for living environment is also getting higher and higher, and more and more people pay attention to the protection of urban environment. Our lawn construction has obtained rapid development, such as city landscaping, golf course, football field, tennis court, racetrack, rivers, highways, railways and other transportation and water conservancy facilities all need high quality lawn. As you all know, the lawn can beautify the environment, soil consolidation, slope protection, purification of air and so on. In the United States, the lawn industry has become one of its ten pillar industries. In all kinds of lawn maintenance work, the lawn pruning work is the most heavy, not only boring, but also repetitive, usually need to consume a lot of manpower and material resources. Therefore, the development of lawn means a large demand for new unmanned mowing vehicles. Therefore, a new intelligent robot is designed in order to solve the above problems.

Since mobile robots have been used in a large number of situations for the tasks that humans could not accomplish and to increase efficiency, it is inevitable that path planning and trajectory tracking control of robot movements have become significant over time. The objective of path planning for mobile robots is to find a collision-free path from a starting point to a target point and to optimize it with respect to certain criteria [1-2]. The methodologies for the path planning problem are mainly categorized into classical and heuristic approaches. The general classical methods, including roadmaps, cell decomposition, or mathematical programming, have dominated this research area in the past [3-5]. Different approaches of predictive control can be found for the trajectory tracking problem for mobile robots. For holonomic mobile robots, Araujo et al. presents a methodology for state feedback model predictive control synthesis based on a cost function developed over finite horizon and linear matrix inequalities framework [6]. A Predictive control strategy for trajectory tracking of differential drive mobile robots is proposed, where the mathematical model of dynamics and kinematics of the mobile robot based on first principle approach was considered [7]. No-linear and other predictive controllers are also applied in mobile robots, as can be seen in Backman et al [8], Leena et al [9] and Boukens et al [10].

Due to the intelligent mowing robot has a minimum turning radius, and the minimum turning radius is greater than half of the cutting table width, so if designing the path planning algorithm completely according to the traditional roundabout path planning, it will have the defect of large leakage area in the steering area. And the previous trajectory tracking algorithms have a nonlinear problem that is difficult to solve. In summary, in order to design a simple path planning and trajectory tracking algorithm, the article is organized in the following sequence. In Section 2 and Section3, we present the system structure and kinematics model of the intelligent mowing robot. Then the roundtrip straight line path planning algorithm and its traversal path equations are respectively designed in Section 4. We design a simple trajectory tracking algorithm in Section 5 Thereafter, the simulation experiment and prototype experiment are carried out in Section 6.

II. LARGE INTELLIGENT MOWING ROBOT

The large intelligent mowing robot studied in this paper is an

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integrated robot system which integrates environment perception, dynamic path planning and behavior control. It is mainly used in airport, golf course, pasture and so on. Four-wheel drive chassis is used in the mowing robot, and a large cutting table is embedded in the body of robot. The hybrid oil and electric power scheme is adopted, including gasoline engine, generator, AC/DC charging module, battery pack and power management module. The gasoline engine provides all the power sources, and drives the generator to obtain the direct current to provide power for the walking motor and other equipment on the vehicle. At the same time, it directly provides mowing power to the cutting table. GPS-RTK navigation equipment is used to obtain accurate position and course information of unmanned mower for path planning and precision navigation. The surrounding environment information of mower is acquired by using radar sensor, which is used to avoid obstacle. The embedded intelligent controller of robot controls the motion of the vehicle, and collects GPS navigation information acquisition, obstacle avoidance sensor information for path planning, navigation, trajectory tracking and so on. The control signal is sent to the corresponding actuator, and the real-time status information is returned to the remote monitoring terminal.

The structure diagram of the large intelligent mowing robot system is shown in Fig. 1, which consists of the following parts.

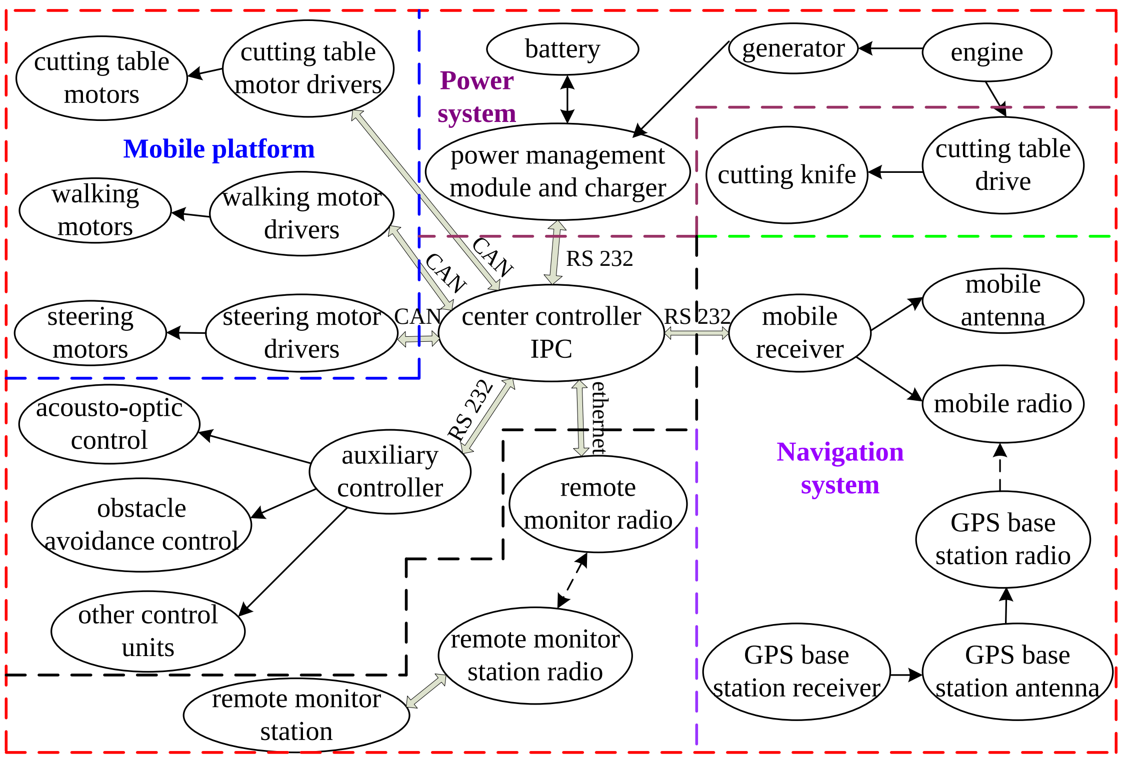

Fig. 1 Structure diagram of the autonomous unmanned mowing robot system

(1) Mobile platform

The mobile platform includes chassis mechanism, walking executive mechanism, steering executive mechanism and height adjustment mechanism of the cutting table. The walking executive mechanism, steering executive mechanism and height adjustment mechanism of the cutting table all consist of DC servo motors reducer and motor driver. A total of nine sets of motor drivers are connected by CAN bus communication mode for unified control. The mechanical structure of autonomous unmanned mower is shown in Fig. 2. Its chassis is driven by four sets of DC motors driving four wheels, and the front two wheels control the steering of the vehicle. The height of the cutting table can be adjusted from eight centimeters to thirty centimeters.

(2) GPS-RTK navigation technology

The robot uses GPS-RTK navigation technology to obtain accurate position and course information of unmanned mower for path planning and precision navigation. Navigation system shown in Fig. 3 consists of GPS mobile station and GPS base station. The base station including satellite antenna, base station receiver and transmitting radio station is placed in the fixed position. The mobile station including the satellite antenna, the mobile station receiver and the receiving radio station is placed on the mower. The GPS-RTK navigation system consisting of GPS-RTK base station and mobile station can achieve pinpoint of centimeter level. The functions of the two stations are as follows:

1) GPS-RTK base station obtains the fixed point position signal through single GPS device, and sends the differential signal to the mobile station to carry on the differential computation. The GPS-RTK base station consists of base receiver, satellite signal receiving antenna, digital radio, digital radio antenna, 12V DC power supply equipment and so on.

2) GPS-RTK mobile station performs differential operation to obtain pinpoint of centimeter level based on the position

information obtained by the mobile station and differential position signals transmitted by the base station. The construction of the GPS-RTK mobile station requires GPS-RTK receiver, two satellite antennas, digital radio receiver, digital radio antenna, 12V DC power supply and vehicle.

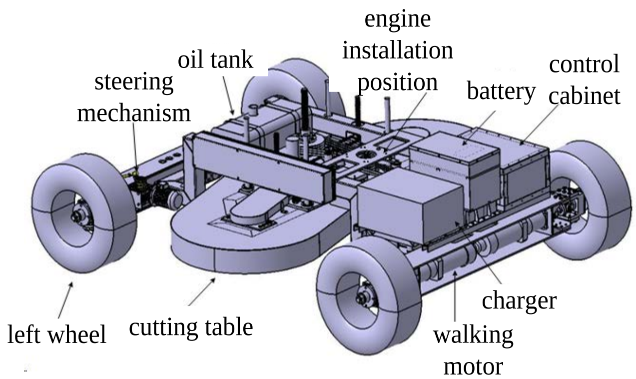

Fig. 2 Mechanical structure of autonomous unmanned mower

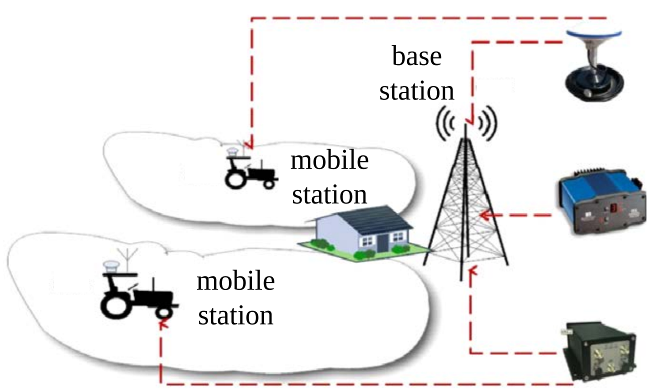

Fig. 3 Navigation system

(3) Control system

The industrial personal computer or mobile intelligent controller is used to build the center controller of robot which is used to output motor drive instructions, collect GPS navigation information, remote monitoring communication information, power management system data and auxiliary control instructions. Auxiliary control module includes sound and light control, obstacle avoidance, remote control interface and engine control. The interface structure of the mower control mainly includes GPS communication interface, remote monitoring communication interface, motor communication interface, handshake communication interface and AI, DI, DO communication interface. Each interface function is as follows:

1) GPS communication interface is mainly used to collect accurate positioning information of GPS output.

2) The remote monitoring communication interface is mainly connected with the remote monitoring communication station, which can send the real-time state to the remote monitoring terminal and receive the control command of the remote monitoring terminal.

3) The motor communication interface is used to send control commands to the motor of the walking, steering and cutting table.

4) The handshake communication interface is used to judge whether the industrial computer crashes or not and executes the corresponding exception handling actions.

5) The AI, DI and DO communication interfaces used to realize the functions of analog acquisition, switch collection and output are built by the special serial port control board module.

(4) Power system

The power system scheme of unmanned mower is shown in Fig. 4. The power system of unmanned mower adopts hybrid oil and electric power scheme, which consists of gasoline engine, generator, charger, battery pack and power management module. The gasoline engine provides total power source. It provides the mowing power directly to the mower cutting table through the transmission mechanism, and connects the generator through the belt to output the direct current and charge the battery pack. Finally, the power of mower and the electric equipment on the vehicle are jointly supplied by the generator and the battery pack. The output voltage of the generator is AC 220V, and the output DC 180V of the charger is supplied to the walking motor and other electrical equipment. When the generator fails or fails to work, the power is directly supplied by the battery pack.

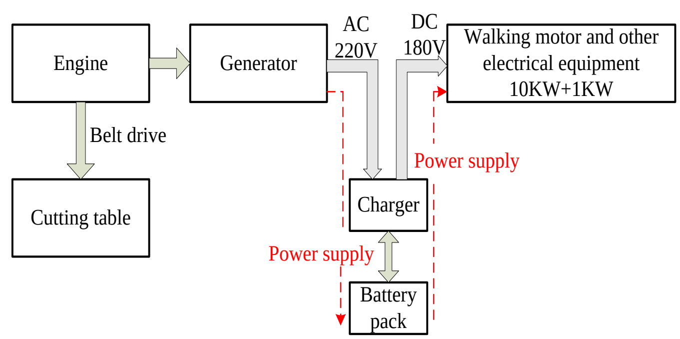

Fig. 4 Power system scheme of unmanned mower

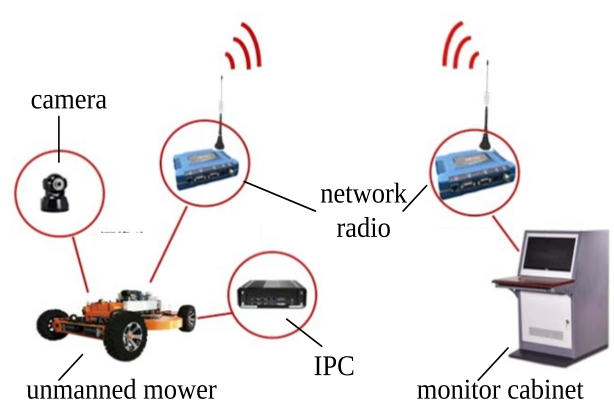

Fig. 5 Remote monitoring schematic diagram of unmanned mower

(5) Remote monitoring system

The ordinary PC is used to build remote monitoring terminal of unmanned mower. The video surveillance equipment is installed on the unmanned mower to obtain video monitoring information, and the video signal, mower status and other information transmitted to the remote monitoring terminal through high performance digital radio. At the same time, we can develop the corresponding application software on the remote monitoring terminal. As shown in Fig. 5, the remote monitoring schematic diagram of unmanned mower is adopted, and the high performance network radio is used as the remote communication medium. The remote monitoring system is mainly composed of two communication links, one of which is the common link, mainly used to transfer state information and control instructions, can realize half duplex communication. The other one is the special real-time video transmission link, can realize one-way communication.

III. KINEMATICS MODEL

The vehicle body structure diagram of intelligent mowing robot is shown in Fig. 6, where *L* is the axle center distance between front wheel and rear wheel, *C* is the axle center distance between left wheel and right wheel, *R* is turning radius, *V* is the velocity of vehicle body, *B* is the vertical distance between mass center and left wheel axle.

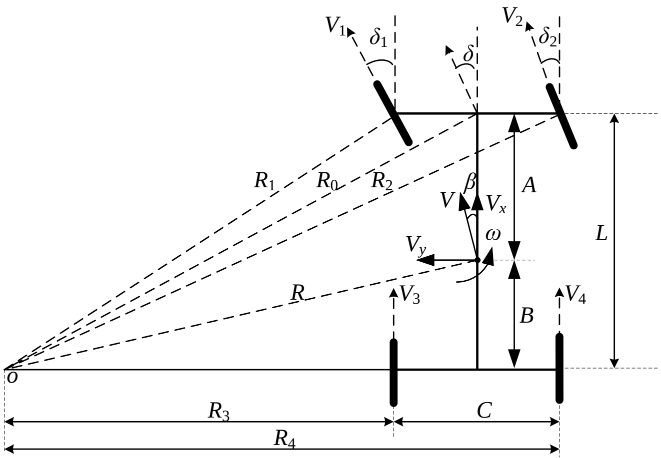

Fig. 6 Body structure diagram of intelligent mowing robot

Let the rotation angles of left front-wheel and right front-wheel are δ_1 and δ_2 respectively. According to Ackerman steering differential model, the geometrical relationship can be displayed as:

$$\tan\delta_1 = \frac{L}{R_3}, \tan\delta_2 = \frac{L}{R_3 + C} \quad (1)$$

According to the Figure 6, the geometrical relationship of *R* can be written as:

$$R = \sqrt{(R_3 + \frac{C}{2})^2 + B^2} \quad (2)$$

Let the vehicle body is rigid body, so the angular velocity of each point is equal. Based on Ackerman model, the velocity of left front-wheel, right front-wheel, left rear wheel and right rear wheel can be calculated as:

$$\begin{cases} V_1 = \frac{L\delta \sin_1}{R} V \\ V_2 = \frac{\sqrt{(R_3 + C)^2 + L^2}}{R} V \\ V_3 = \frac{R_3}{R} V \\ V_4 = \frac{R_3 + C}{R} V \end{cases} \quad (3)$$

IV. PATH PLANNING

Path planning is the key factor to achieve high efficiency working ability for mowing robot. The consumed energy and time are different for different walking paths. The longer walking path and the more turning times, the more energy and time consumed by the mowing robot. Considering the task of mowing robot and its blade center does not coincide with the motion center, it is not suitable to use random and spiral path planning algorithm. Roundabout path planning algorithm is simple, but the number of turns leads to lower efficiency. However, the mowing robot is mainly used in the large lawn of the airport. Compared with other open lawn environment, the large lawn of the airport has obvious characteristics, such as the static structure environment, no large obstacle and not allowed to be modified at will. Therefore, the paper proposes a new path planning algorithm focusing on the efficiency based on the traditional roundabout path planning algorithm.

The path planning adopts the method of polygon working area, and the autonomous walking mainly adopts the straight line without considering the curve way except the steering. The mowing robot collects the working area boundary location coordinates through the GPS, obtaining the polygon boundary vertices and boundary line equations. The angle of polygon working area is not more than 180^o, otherwise it is split into multiple polygons. The first point of the polygon is set as the origin of coordinate, the connection of the first point and the second point is set as the y' axis shown in Fig. 7. The coordinate transformation formula is as follows:

$$\begin{bmatrix} x_i' \\ y_i' \end{bmatrix} = \begin{bmatrix} \cos\gamma & -\sin\gamma \\ \sin\gamma & \cos\gamma \end{bmatrix} \begin{bmatrix} x_i - x_0 \\ y_i - y_0 \end{bmatrix} \quad (4)$$

Where x_i and y_i are respectively the coordinate value of the *i*-th point in the *o*-*xy* terrestrial coordinate system, x_i' and y_i' are respectively the coordinate value of the *i*-th point in the

o'-$x'y'$ regional coordinate system, x_0 and y_0 are respectively the coordinate value of the first point in the o-xy terrestrial coordinate system, γ is the angle between the y axis and the y' axis, and clockwise is the positive direction.

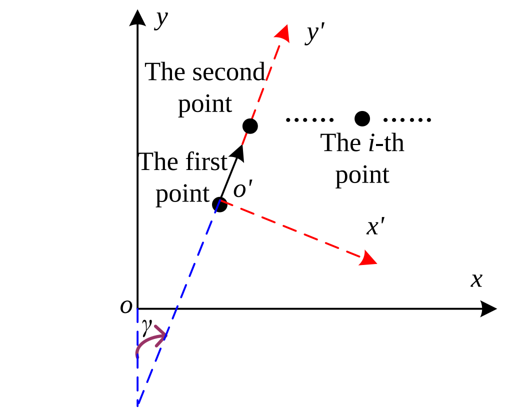

Fig. 7 Schematic diagram of coordinate transformation

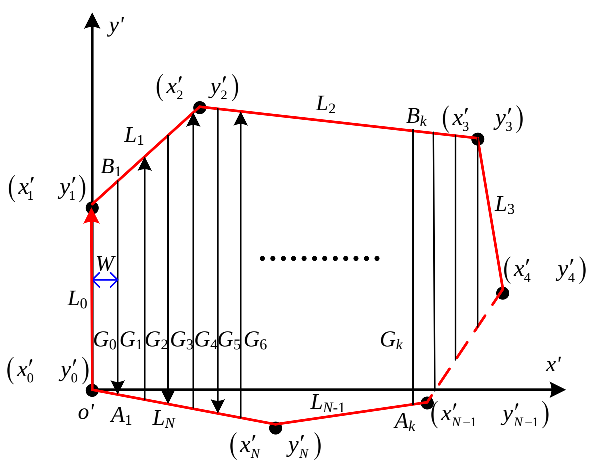

Fig. 8 Schematic diagram of polygon region planning

The path planning of roundabout type is simple and unified. The movement of mowing robot is easy to control, and the energy consumption is the minimum. It is the optimal path planning method for mowing robot. However, due to the intelligent mowing robot has a minimum turning radius, and the minimum turning radius is greater than half of the cutting table width, so if designing the path planning algorithm completely according to the traditional path planning algorithm will lead to miss cutting in the steering area. Therefore, the paper proposes the roundtrip linear path planning algorithm to complete the mowing work for robot.

Let the boundary point information of work area has been obtained by GPS, and completed the transformation calculation according to the (4). The coordinates (i.e. $(x_0' \quad y_0')$, $(x_1' \quad y_1')$, $(x_2' \quad y_2')$, $\cdots$, $(x_N' \quad y_N')$) of each point in the regional coordinate system are shown in Fig. 8. The planned path is the intersection of the straight line G_K and the boundary line L_i. According to the coordinates of each point in the regional coordinate system, the boundary line L_i in the regional coordinate system is divided into the following two cases.

Case 1. If $i \le N$-1, the boundary line equation is as follows:

$$(y_i' - y_{i+1}')x' + (x_{i+1}' - x_i')y' + (x_i' y_{i+1}' - x_{i+1}' y_i') = 0 \qquad (5)$$

Case 2. If $i=N$, the boundary line equation is as follows:

$$(y_N' - y_0')x' + (x_0' - x_N')y' + (x_N' y_0' - x_0' y_N') = 0 \qquad (6)$$

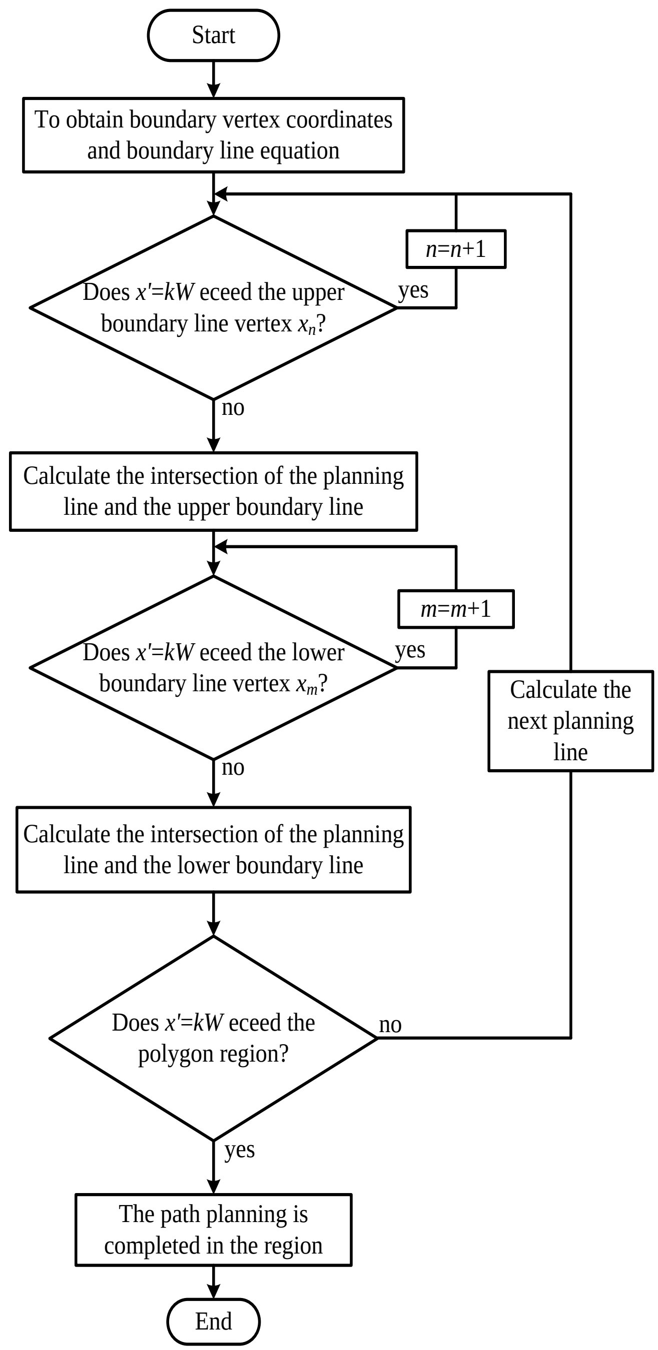

Fig. 9. Flow chart of line path planning in polygon region

The equation of the line G_K in the regional coordinate system is $x'=kW$, so the intersection of the straight line G_K and the boundary line L_i can be obtained by (5) and (6). After the coordinates of each intersection point are calculated, the path planning of mowing robot can be carried out according to the flow chart shown in Fig. 9.

V. TRAJECTORY TRACKING CONTROL ALGORITHM

The relationship between the intelligent mowing robot and tracking linear trajectory is shown in Fig. 10. It is determined by the deviation information (i.e. angel deviation α and distance bias d). The paper define the left deviation as positive and the right deviation as negative, so the relationship can be divided into the following situations: (1) α=0, d=0; (2) α>0, d=0; (3) α<0, d=0 ; (4) α=0, d<0; (5) α>0, d<0; (6) α<0, d<0; (7) α=0, d>0; (8) α>0, d>0; (9) α<0, d>0. Let the mowing robot's running velocity is v, the GPS refresh frequency is f, the steering angle of steering wheel is θ (left turn is positive, right turn is negative), the maximum steering angle is θ_{max}, and the minimum and maximum distance bias are d_{min} and d_{max} respectively.

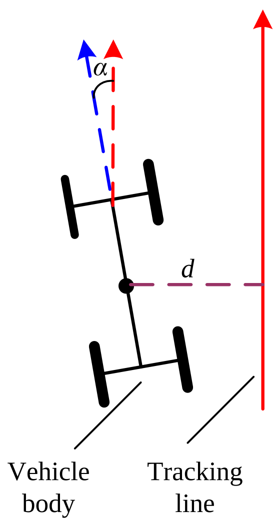

Fig. 10 Position between robot and planning path

Due to the existence of many nonlinear and uncertain factors, it is difficult to achieve satisfactory correction effect by using the conventional control method. Fuzzy logic control and neural network technology do not need precise mathematical models between input and output, which is an effective way to solve these problems. However, the quality of algorithm is closely related to the selection of experience parameters, and there is no uniform design standard. Therefore, the paper designs a simple trajectory tracking algorithm based on the operation characteristics of the intelligent mowing robot, and it is designed as follows.

When the intelligent mowing robot moves forward, it is divided into the following five cases:

Case 1: when $|d|\leq d_{min}$, the intelligent mowing robot adjusts the direction by (7):

$$\theta = -(\theta_{max}\frac{d}{d_{min}} + \alpha) \tag{7}$$

If $|\theta|>\theta_{max}$, then taking $|\theta|=\theta_{max}$.

Case 2: when $d_{min}<d<d_{max}$, the intelligent mowing robot adjusts the direction by (8):

$$\begin{cases} \theta = \theta_{max} & |\alpha| \geq \pi/2 \\ \theta = -\theta_{max} & 0 < \alpha < \pi/2 \\ \theta = -\alpha - \theta_{max} & -\pi/2 < \alpha \leq 0 \end{cases} \tag{8}$$

Case 3: when $d>d_{max}$, the intelligent mowing robot adjusts the direction by (9):

$$\begin{cases} \theta = \theta_{max} & |\alpha| \geq \pi/2 \\ \theta = -\theta_{max} & |\alpha| < \pi/2 \end{cases} \tag{9}$$

Case 4: when $-d_{max}<d<-d_{min}$, the intelligent mowing robot adjusts the direction by (10):

$$\begin{cases} \theta = -\theta_{max} & |\alpha| \geq \pi/2 \\ \theta = \theta_{max} & 0 < \alpha < \pi/2 \\ \theta = -\alpha + \theta_{max} & -\pi/2 < \alpha \leq 0 \end{cases} \tag{10}$$

Case 5: when $d<-d_{max}$, the intelligent mowing robot adjusts the direction by (11):

$$\begin{cases} \theta = -\theta_{max} & |\alpha| \geq \pi/2 \\ \theta = \theta_{max} & |\alpha| < \pi/2 \end{cases} \tag{11}$$

When the intelligent mowing robot moves backward, the trajectory tracking algorithm is similar to the forward direction. But it need to adjust the angel deviation α according to the (12):

$$\begin{cases} \alpha' = \alpha + \pi & |\alpha| \leq \pi \\ \alpha' = \alpha + 2\pi & \alpha < -\pi \\ \alpha' = \alpha - 2\pi & \alpha > \pi \end{cases} \tag{12}$$

VI. EXPERIMENTAL ANALYSIS

A. *Simulation Experiment and Analysis*

Let boundary points collected by GPS are as follows: (0, 0), (0, 50), (50, 100), (120, 50), (150, 0), (50, -50). The boundary points are connected with straight line into a polygon working area. Through analysis found that the angles of polygon working area are all not more than 180^{o}. According to the path planning algorithm, the results of path planning are shown in Fig. 11.

Let the start point coordinate of the mowing robot is (-1, 0), the single cut width is 1.2m, the end point coordinate of the mowing robot is (8.4, 0), the initial angle deviation is zero, the velocity of robot is v=1.5m/s, the refresh frequency of GPS is f=5Hz. According to the above trajectory tracking algorithm, the simulation results are shown in Fig. 12, where the cutting leakage rate is 7.15%.

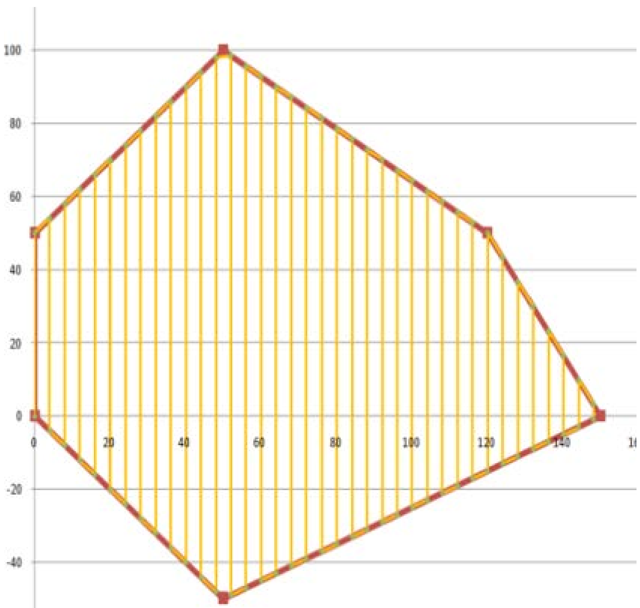

Fig. 11 Simulation experiment of path planning

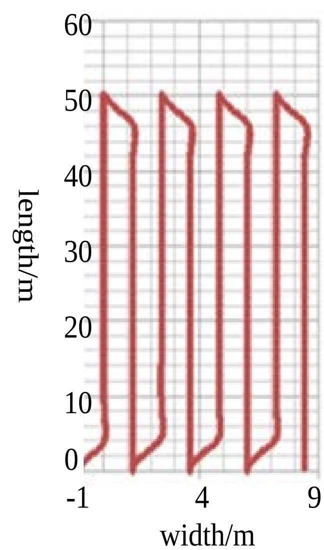

Fig. 12 Simulation of robot with forward and backward

B. *Prototype Experiment and Analysis*

At present, all works of intelligent mowing robot's mechanical processing, assembly and electrical wiring have been completed. After installation, the intelligent mowing robot is shown in Fig. 13. Its largest cutting width is 2.4m.We take a mowing area where path has been planned. The start point coordinate of the mowing robot is (0, 0), the single cut width is 2m, the end point coordinate of the mowing robot is (18, 0), the initial angle deviation is zero, the velocity of robot is v=1.5m/s, the refresh frequency of GPS is f=5Hz. According to the above trajectory tracking algorithm, the prototype experiment results are shown in Fig. 14, where the cutting leakage rate is 8.89%. It is consistent with the simulation results, which shows that the trajectory tracking algorithm is correct and feasible.

Fig. 13 Mowing robot for large airport lawn

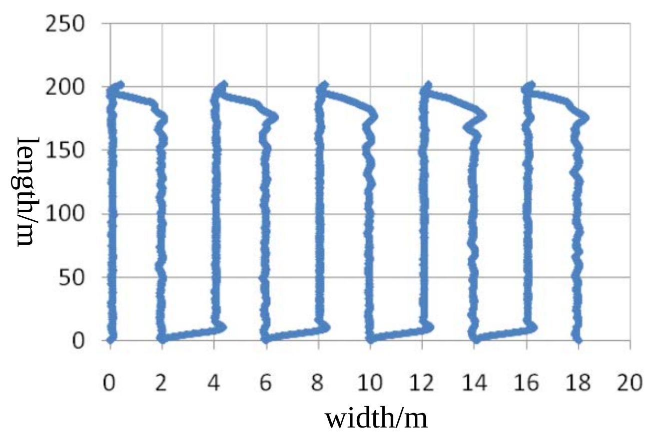

Fig. 14 Experiment of robot with forward and backward

VII. Conclusion

The path planning and trajectory tracking control of a newly designed intelligent mowing robot are studied and the following conclusions are obtained.

(1) Based on the location information collected by GPS, the modeling of polygon working area is completed and the roundtrip linear path planning algorithm is designed in the established polygon working area. Compared with the traditional circuitous path planning algorithm, it can overcome the defect of cutting leakage in the steering area.

(2) Based on the angel deviation and distance bias of mowing robot, a new trajectory tracking algorithm is designed. The convergence of trajectory tracking algorithm is verified by simulation experiment. According to the system design, the prototype is produced and manufactured. The practicability of the path planning and trajectory tracking algorithm is verified by prototype test.

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