Application of Fuzzy Control Algorithm in Power Substation Inspection Robot

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Abstract - This paper presents the electric power substation equipment's inspection by mobile robot which is considered as one the most fields of research, and addresses the power substation inspection robot, which is used in many power substations in China. The reliability, safety and intelligence of power substation have been greatly developed. However, when inspecting the task, the power substation inspection robot may appear oscillation, sway or other unstable movements. To solve these unstable movements, the system architecture and the inspection task planning of power substation inspection robot are presented. Then through building the robot's mathematical model and analyzing robot's motion characteristics and inspection path, a novel fuzzy control algorithm for substation inspection robot path planning is also proposed that combines multi-sensor fusion magnetic path navigation and RFID orientation technology in strong electromagnetic environment of substation. The proposed approach can better resolve the problem of posture oscillation and wagging tail of the substation inspection robot, while adjusting pose. So the inspection robot could be working autonomously, stably and precisely. The simulation and experiments show that the proposed method is the effectiveness and feasibility for path planning of inspection robot.

Keywords: Power substation, Inspection robot, Multi-sensor fusion, RFID technology, Path planning, Fuzzy logic.

I. INTRODUCTION

Power substation is the kernel of all electric grids, and thus inspecting equipment in substation is an inevitable method to ensure the secure process of the electric grid. Because of the high-speed growth of national economy, the scale of the electric system is enlarging which indicating the increasing requirement of the system stability [1-5]. However, the current inspection method is operated by human beings, which needs high workload and cannot ensure the inspection quality. With the development of robot technology and visual inspection methods, it is possible to inspect equipment by mobile robot in power substation which can remarkably improve the quality of inspection, lower the workload of substation workers, reduce the risk to workers by replacing their work under severe weather condition, and finally achieve the goal of unmanned inspection [6-7].

The power substation inspection robot, working in the environment of the substation that is getting more complex, and is always unknown, dynamic, unstructured and strong electromagnetic interference, is different from general industrial robots. Besides, the information that can be perceived by the sensor is limited and exists the fragmentation and uncertainty, so that it is more difficult for path planning of robot to complete inspection task. When power inspection robot inspects tasks, it is easy to slid and deviate from the running track for other reasons. And when adjusting the robot attitude, there will be also easily excessive or improper. So the robot will run unstably, swinging back and forth, which will affect the accuracy of the robot. As we all know, path planning is the basis for the completion of the inspection tasks of power substation inspection robot [8-9]. The so-called path planning, based on sensors' environment information, is to plan a safe and stable path, and perform quickly and efficiently. The path planning of inspection robot mainly solved three problems, which are as follows:

- According to prescribed paths, power substation inspection robot should move from initial node to the goal node;
- Power substation inspection robot could bypass or climb over obstacles and it will go through the task points where necessary;
- The path of power substation inspection robot should be optimized under the fulfilled inspection task premise.

So far there are a lot of achievements in the field of the research on path planning. In static environments, Yi et al [10] suggest a map building algorithm of simultaneous localization and path planning based on the potential field. With the help of a potential field theory and by conducting simultaneous localization and mapping, robot can locate its movement control discipline. But this method is fit for the situation that regarding the landmarks also as obstacles is given. Jeevamalar [11] used a genetic algorithm to solve the problem of robotic path planning and discussed a search strategy based on models of evolution. Yang et al [12] proposed a novel biologically inspired tracking control approach for nonholonomic mobile robot to real-time navigation by integrating a backstepping technique and a neurodynamics model. And Lyapunov stability theory is used to guarantee the stability of the robot control system and the convergence of tracking errors to zeros. The proposed approach is capable of generating smooth continuous robot control signals with zero initial velocities. Using ultrasonic sensors to obtain the information about obstacles and goals, Chen et al [13] apply fuzzy algorithm to mobile robot path planning strategy, which can solve the optimal path planning problem. Amoozgar et al [14] devised two further fuzzy controllers to adjust the linear/angular velocity of the robot, and an appropriate heading angle of robot at each instant is provided. Then a heading angle scheduler based on a two-stage fuzzy logic system is proposed, which are several advantages in terms of its robustness and tracking performance. However, many path planning methods cannot be used in substation environment. With the modern computing technology in mobile robot path programming, more intelligent path algorithms [15-16], such as neural networks, fuzzy logic, information fusion and other algorithms of combining methods, have been studied and used in robot path planning widely.

In this paper, aiming at the key technology of substation inspection robot research, the system architecture and the inspection task planning of power substation inspection robot are presented to meet the requirements of the substation environment, inspection tasks, stability and flexibility. And for the unstable movement, the novel fuzzy control algorithm is used to achieve path planning, meanwhile taking advantage of multi-sensor fusion magnetic track navigation and RFID orientation technology. The fuzzy algorithm and information fusion technology have excellent performance in uncertainty information processing, which make them have a good application in the robot path planning. Inspection robot, with single magnetic navigation, is unable to get the position coordinates. Therefore, the RFID technology positioning is also used. At present, the magnetic track navigation of multi-sensor fusion (Road surface magnetic track with RFID tag positioning) is the most reliable way of a navigating and positioning, applied to strong electromagnetic environment, all-weather conditions in substation, positioning accuracy. The driving route information will be got by detecting the magnetic track in real-time. Then the fuzzy control algorithm, which provides a more reliable method in a substation complex environment, is used in the magnetic track path planning, since this method has good real-time and many other advantages. Power substation inspection robot, based on fuzzy control algorithm and combined with multi-sensor fusion magnetic path navigation and RFID orientation technology, can be working autonomously, stably and precisely in practical application. The problem of posture oscillation and wagging tail of the substation inspection robot has been resolved. Besides, the robot's intelligence will be improved without the assistance of human.

II. SYSTEM MODEL OF POWER SUBSTATION INSPECTION ROBOT

Power substation inspection robots [3,6,17], used in many power substations in China, improve the automatic and intelligent level of the power substation inspection and the safety of the substation, which can complete all-weather outdoor work including motion control, image acquisition, equipment process, autonomous navigation, accurate positioning, wireless communication and the automatic charging and other functions. The substation inspection robot, based on visible light camera, thermal infrared imager and pickup, is combined with image processing, pattern recognition technology. Also, it can compare the sound characteristics of the library at the same time, which can automatically identify and alarm the appearance status (Division and other abnormal appearance knife and abnormal operation inside the device).

The movement of substation inspection robot is the basis for completing stable job [6,18]. In this paper, the substation inspection robot carrier uses wheeled dolly construction which has two front wheels controlled by the drive motor, and two rear casters. This simple structure is easy to control the movement and direction of the inspection robot, and achieve small turning radius by one of the driving wheel. The casters play a supporting and auxiliary driving and steering function to make the substation inspection robot more flexible. The movement of inspection robot is achieved by the speed and direction of rotation of the drive motor, using of differential drive motors to achieve steering and regulating pose and other functions. This machine has strong adaptability to complex environment with simple structure, easy processing, no sideslip, linear motion and well steering properties.

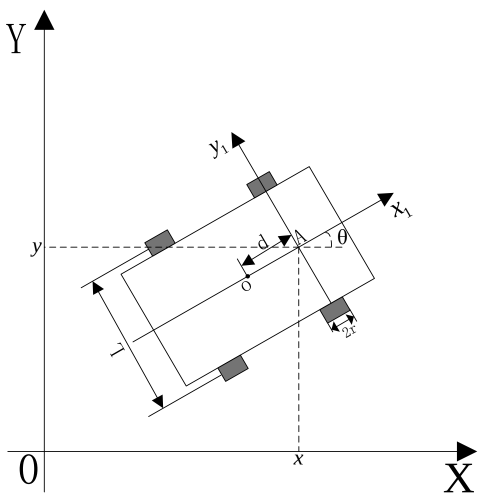


Fig.2.1 Motion diagram structure model of the power substation inspection robot

In order to accurately locate the equipment which inspected in the substation, the linear degree and the positioning accuracy of the inspection robot posture is required. So the inspection robot's mathematical model is build [12,14], shown in Fig 2.1, which shows these two coordinate systems: the global coordinate system *{X O Y}* and the local coordinate system $\{x_1, o, y_1\}$,where x_1 is the driving direction, *o* is the robot center point, and y_1 is the robot lateral direction. Substation inspection robot uses two drives, there will be only linear or circular motion. When the left and right wheels have speed consistent, inspection robot will do linear motion; when the left and right wheels speed inconsistent, inspection robot will do circular motion by a certain radius. Therefore, the purpose of inspection robot motion can be controlled through controlling the speed of wheels.

Substation inspection robot's position, velocity and angular velocity are represented by $\left((x, y, \theta), v, \omega\right)$. Then the equation of motion is obtained as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \upsilon \\ \omega \end{bmatrix} \qquad (1)$$

$$P = \begin{bmatrix} \upsilon \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & \frac{-r}{L} \end{bmatrix} \cdot \begin{bmatrix} V_R \\ V_L \end{bmatrix} \qquad (2)$$

Where v represents the center of substation inspection robot velocity, v_L represents the velocity of the left driving wheel, v_R represents the velocity of the right driving wheel, L represents the width of the left and right wheels and ω represents the angular velocity of the center. When $V_R = V_L$, $\omega = 0$, inspection robot will drive in straight line; When $V_R = -V_L$, inspection robot will rotary motion around the center of mass, and reverse driving can be realized. When $V_R \neq V_L$, inspection robot will do a certain radius ρ of the circular motion, ρ formula is as follows:

$$\rho = \frac{\upsilon}{\omega} = \frac{\mathrm{L}(V_L + V_R)}{2(V_L - V_R)} \qquad (3)$$

By formula (1) and (2), the linear and angular velocities formulas can be derived final substation inspection robot's kinematics equation as follows:

$$P = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\theta & \frac{r}{2}\cos\theta \\ \frac{r}{2}\sin\theta & \frac{r}{2}\sin\theta \\ \frac{r}{L} & \frac{-r}{L} \end{bmatrix} \cdot \begin{bmatrix} V_R \\ V_L \end{bmatrix} \qquad (4)$$

The formula (4) shows that: substation inspection robot's pose adjustment and movement can be realized by controlling the speed of the left and right wheels (magnitude of V_R, V_L).

The constrain equation that the substation inspection robot wheel can only roll and not slip in lateral direction is as follows:

$$\dot{x}\sin\theta + \dot{y}\cos\theta - d\dot{\theta} = 0 \qquad (5)$$

III. DESIGN OF FUZZY CONTROL ALGORITHM FOR POWER SUBSTATION INSPECTION ROBOT

When in the inspection working, substation inspection robot is easy to slid and deviate from the running track for other reasons. When adjusting the inspection robot, adjustment will be easily excessive or improper. So the robot will run unstably, swinging back and forth, which will affect the accuracy of the robot. In order to get rid of this situation, the fuzzy control algorithm is applied to inspection robot path planning in this paper. The substation inspection robot can autonomously completely reasoning, planning and control by this method. The more stable and more efficient of high precision inspection work can be achieved.

3.1 Principles and Analysis of Fuzzy Control Theory

Appling the fuzzy control algorithm [19-20], general collection which only take two values (0 and 1) is extended to any real number between 0 and 1. The disadvantage existed in the traditional control and navigation issues can be overcame. In the more complex environment of substation, fuzzy control system makes movement speed of the substation inspection robot change gradually and won't appear sudden change, so that the substation inspection robot runs with large real-time, superiority as well as good robustness.

The wheeled substation inspection robot is introduced, and whose moving accuracy mainly depends on the accuracy of the wheel's speed difference. Through detecting the distance between the robot and magnetic track timely and detecting the embedded RFID tags in the inspection paths, the RFID reader reads the tag information. Then the location and tag information will be sent to the IPC, IPC issues instructions to control the drive motor speed in real time. The stopping, turning, speed and adjustment of the position can be achieved. The distance between the robot and magnetic track and the RFID tags information is detecting constantly to make inspection robot always move along the magnetic path. Then the minimum error of movement can be realized. In fact, the active wheels can be expressed by the formulas: $V_L = V \pm V_E$ and $V_R = V \mp V_E$. If drive motor output wants to be controlled by fuzzy control algorithm, the offset distance between the magnetic track and the inspection robot should be known. So the position information between inspection robot and magnetic track needs be detected in real-time.

In this paper, In front of the substation inspection robot carrier reasonably places seven sensors (turn left to right: F1, F2, F3, F4, F5, F6, F7). For example, when the F5 sensor detects ground magnetic track, inspection robot posture is the right of micro deviation. Robot posture needs to be finely adjusted to the left, and the mean is that right drive motor speed slightly faster, until the F4 sensor detects ground magnetic track. When substation inspection robot appears the deviation of trajectory, the path diagram is shown in Fig 3.1.

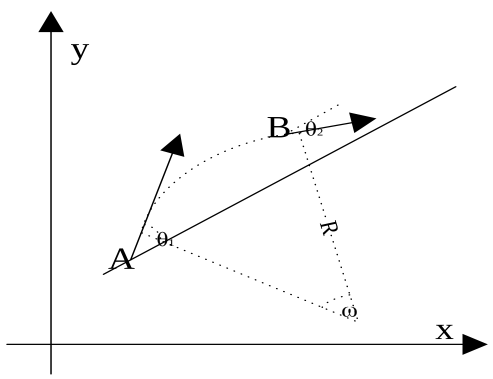


Fig.3.1 Path diagram of substation inspection robot

Substation inspection robot deviates at point A, with the angle θ_1 of the driving direction and magnetic track. Due to the inertia, robot will keep moving. From point A to point B by the time t, substation inspection robot kinematics and characteristics shows that the driving radius of adjustment is R: $R = vt / \omega$. Driving displacement: $l_{AB} = 2R \cdot \sin(\omega / 2)$. The displacement of the magnetic track: $l = l_{AB} \cdot \cos\frac{\theta_1 - \theta_2}{2}$. Robot adjusts the angle θ_2 of point B and magnetic track. Through the sensors real-time feedback of information, the drive motor control the speed of the left and right wheel .The pose of inspection robot will adjust to the next step until the slip angle $\theta = 0$. Substation inspection robot moves precisely along with the magnetic track.

3.2 Design of Fuzzy Controller

The proposed fuzzy control algorithm for substation inspection robot control system is shown in Fig 3.2. The control system consists of fuzzy logic controller, the kinematic model of inspection robot, and a reference trajectory generator. In this paper, for the precision of substation inspection robot patrol operation, two-dimensional fuzzy controller, which may be able to reflect dynamic characteristics of the output in controlled process, is designed by analyzing characteristic of motion and path recognition principle of inspection robot. Position error E that is between the center position sensor (F4 sensor) of inspection robot and magnetic track and its rate EC are determined as an input variable, and the angle of robot's adjustment is determined as an output U. But the angle of adjustment is a position amount, so this angle should be controlled by the speed of two drive motors, using the differential to adjust.

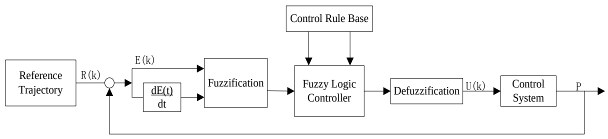


Fig.3.2 Fuzzy control algorithm for substation inspection robot control system

Suppose the negative direction can represent the situation where the substation inspection robot is to the left of the magnetic track, and the positive direction can represent the situation where the substation inspection robot is to the right of the magnetic track. Due to the range of differential drive motors is vary widely, and the substation inspection robot needs high precision, so the fuzzy sets of the error E and its rate EC defined as {NB，NM，NS，ZO，PS，PM，PB}, correspond to{negative big, negative middle, and negative small, zero, positive small, positive middle, positive big}, the fuzzy sets of the controlled quantity U defined as{NB，NM，NS，ZO，PS，PM，PB}, correspond to{left big, left middle, left small, zero, right small, right middle, right big}. the error E and its rate EC are selected for universe as{-6，-5，-4，-3，-2，-1，0，1，2，3，4，5，6}, and the controlled quantity U is selected for universe as{-30，-25，-20，-15，-10，-5，0，5，10，15，20，25，30}.

According to the variation trend of error E and its rate EC, and combining with the control experience and kinetic characteristic of substation inspection robot, the fuzzy rules are designed to eliminate errors. When the error E is small, and its rate EC is constant(EC = 0), inspection robot is running along the magnetic track; When the change of its rate EC is large, the inspection robot is deviation of magnetic trace running, then the angle of inspection robot driving should be adjusted.

Tab.3.1 Fuzzy rule table

U		E						
		NB	NM	NS	ZO	PS	PM	PB
EC	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PM	PS	ZO	NS	NS
	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	ZO	NM	NM	NM	NB	NB

Fuzzy control rules are described by the condition statements of "$If --then$", which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control, and each of conditional statements has "or" relationship. This paper contains 7*7=49 fuzzy rules, describing with fuzzy rule table as shown in Tab 3.1.

Ultimately, the drive motor is controlled. However, the fuzzy quantity cannot be identified, so a certain value should be gotten from the fuzzy sets obtained by fuzzy inference. In this paper, gravity method should be adopted to turn fuzzy control volume to exact value. Formula is as follows:

$$v_o = \frac{\sum_{i=1}^{m} x_i \times u(x_i)}{\sum_{i=1}^{m} u_N(x_i)} \tag{6}$$

Through the linear scaling, the actual output is gotten and exports to the drive motor. According to the kinematics equation, drive motor controls the speed of the wheel by the given actually value. The position of inspection robot can be controlled.

IV. SIMULATION RESULTS

Through the simulation of MATLAB to above fuzzy control system, surface view of input and output of fuzzy inference is acquired, as shown in Fig 4.1. The Fig 4.1 intuitively shows the trend how output variable U changes with input variable E and EC according to the fuzzy rules.

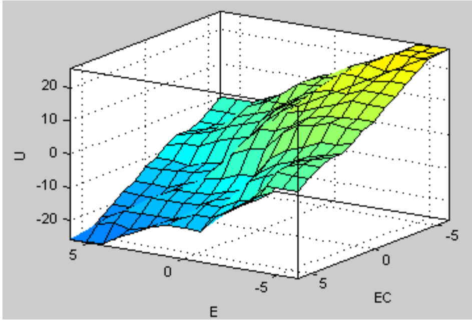
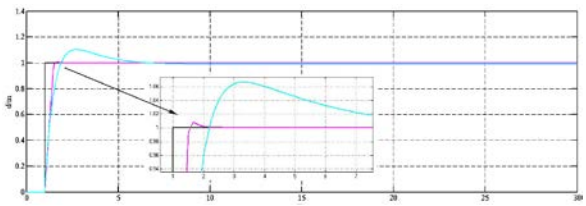
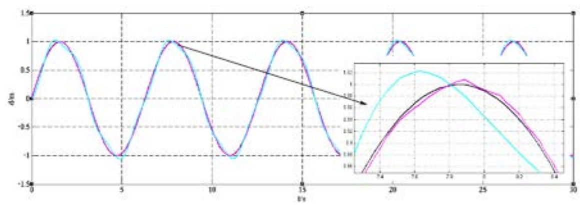


Fig.4.1 Surface view of input and output of the fuzzy inference

Substation inspection robot works in inspection process with mostly straight and turns with a certain curvature of the travel route. In this paper, in order to verify the feasibility and reliability of this theory, through the above algorithm, substation inspection robot moves path is simulated by SIMULINK. Using the step signal to simulate the movement of straight and turn and using the sinusoidal signal to simulate the movement of straight and turn with a certain radian. The simulations are shown in Fig 4.2, and the movement errors of robot are shown in Fig 4.3.

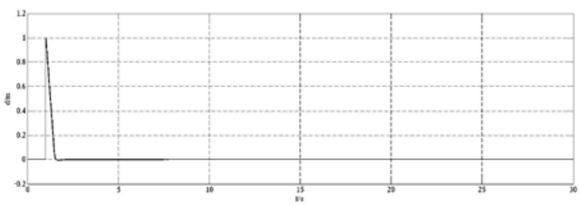


(a) Step signal simulation

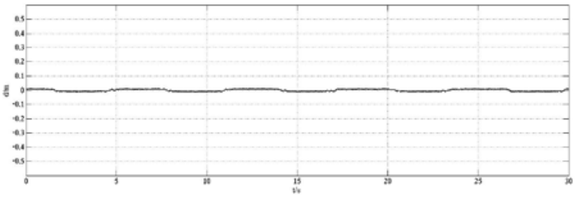


(b) Sinusoidal signal simulation

Fig.4.2 Step signal and sinusoidal signal simulation



(a) The error of step signal



(b) The error of sinusoidal signal

Fig.4.3 The substation inspection robot movement errors

In Fig 4.2, the black line is the route that robot should be moved, and the blue line is the route which moved by substation inspection robot based on PID control, and the red line is the route which moved by substation inspection robot based on fuzzy control algorithm. From Fig 4.2, we can see that the substation inspection robot based on PID control has greater movement error, especially on cornering. However, from Fig 4.3, we can see that the inspection robot appears small deviation error at right-angle, by selected the appropriate quantitative factors. And after a short time adjusting, robot can turn and move with minimal error, following the magnetic track. There is feasible and superiority.

The above simulation results show that inspection robot can move almost minimal errors. Therefore, fuzzy control algorithm for substation inspection robot path planning based on the multi-sensor fusion technology and RFID orientation technology can be more precise along the magnetic track, and complete substation inspection more efficient and quick. The results demonstrate the feasibility and effectiveness of the proposed method.

V. CONCLUSION

This paper introduces the fuzzy control algorithm based the multi-sensor fusion technology and RFID orientation technology for power substation inspection robot path planning. And the proposed method is simulated using MATLAB and tested in the laboratory. As can be seen from the simulation results, in more complex substation environment, using the magnetic track for navigation and RFID orientation technology, substation inspection robot based on fuzzy control algorithm can be able to complete the inspection working quickly and accurately. Its kinetic characteristic and accuracy are higher than other inspection robot. The problem of posture oscillation and wagging tail of substation inspection robot will be overcome effectively. And the robot based on fuzzy control algorithm has a good real-time performance and anti-jamming capability. Then the feasibility and effectiveness of the proposed method can be verified. Therefore, this method has certain advantages, and can meet the actual needs.

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