Optimization of Path Planning for Domestic Sweeping Robots Using Fuzzy PID Control

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Abstract. This paper explores the development of an advanced path optimization method for household sweeping robots, enhancing their operational efficiency and accuracy in diverse and complex environments. With the proliferation of smart home devices, the demand for autonomous cleaning robots that can navigate and clean efficiently across various household layouts has significantly increased. Traditional path planning algorithms often fall short in dynamically changing and cluttered domestic spaces, leading to suboptimal cleaning paths and missed areas. To address these challenges, we introduce a fuzzy PID control approach, integrated with a multi-sensor data regulation system. This innovative method employs fuzzy logic to handle the uncertainty and variability inherent in real-world environments, while the PID control optimizes the robot's movements for precision and responsiveness. The integration of fuzzy logic allows for adaptive threshold setting, which enhances the robot's ability to make real-time decisions based on the continuous feedback from its array of sensors. This paper presents a detailed analysis of the fuzzy PID algorithm's performance in navigating complex paths, demonstrating significant improvements in path efficiency and obstacle avoidance compared to conventional methods. By conducting extensive simulations and real-world tests in various household settings, we establish the robustness and reliability of our proposed model. The results highlight the potential of fuzzy PID control to revolutionize the navigation capabilities of domestic robots, making them more adaptable and efficient in complex environments. This research not only contributes to the field of robotics but also opens new avenues for the application of fuzzy logic in smart home technologies.

Keywords: Sweeping robot, Fuzzy pid algorithm, Robot attitude control, Sensor.

1. Introduction

Robots, as advanced technological embodiments of the latest information technologies such as electronics, the Internet of Things, and computer science, often face operational challenges due to external environmental disturbances. These disturbances can significantly deviate a robot from its intended trajectory, primarily due to the inherent limitations of traditional control systems in resisting interference [1]. This necessitates a robust mechanism that enables immediate detection and correction of such deviations to maintain optimal performance. Among household technologies, sweeping robots are prevalent as intelligent devices designed to autonomously perform indoor cleaning tasks [2]. These robots must navigate complex environments, requiring precise sensing capabilities and effective path planning to avoid obstacles safely. Introducing a fuzzy PID controller into the robot’s route detection and control system can significantly enhance responsiveness to diverse operational scenarios. By integrating inputs from various sensors to determine fuzzy thresholds, a fuzzy PID controller helps to compensate for the uncertainties and variabilities in target tracking. This adaptation not only addresses the nonlinearity in the system but also improves the robot’s ability to maintain its course in the face of unpredictable external influences [3].

Thus, the implementation of fuzzy PID control in robotic systems represents a critical advancement in ensuring that robots can perform their designated tasks efficiently, even in dynamically changing environments. This approach not only bolsters the robot's adaptability but also enhances its reliability, making it an indispensable tool in the progressive automation of routine household chores.

2. Related Theory and Optimization Analysis

2.1. The Development Process of The Existing Sweeping Robot

In recent years, artificial intelligence has penetrated into every corner of our society. Take the home sweeping robot as an example, at present, the sweeping robot is the only autonomous mobile, widely used in thousands of households [4]. Since 2009, the domestic brand 'Covos' launched the sweeping robot 'Di Bao series', the research and development of the sweeping robot in China has also opened a new chapter. Since then, laser navigation and visual navigation have been applied to products by developers, greatly improving the obstacle avoidance ability of products and improving the robot's perception of the surrounding environment. Until now, the technical algorithm of the sweeping robot is increasingly mature, which can realize more rich functions such as 'sweeping and dragging integrated' and automatic cleaning, but with the development of society, the working environment of the sweeping robot is becoming increasingly complex [5]. From sweeping robot cleaning path, the layout is different, some house put clean, general robot can quickly determine the cleaning route, but some house items put disorderly, there may be children, pets, to quickly determine the cleaning route and immediate target, at the same time avoid robot encounter human or fragile items, need robot rapid detection and corresponding real-time movement [6].

2.2. Introduction of The Fuzzy PID Theory

At present, PID control is diffusely used because it has the simple operation and good reliability. Using PID control system, The PID system equation is defined as:

$$u(t)= kp\ e(t) + ki\int_0^t e(t)dt + kd\frac{de(t)}{dt} \quad (1)$$

In the above equation, kp, ki and kd are the symbol of proportional, integral and differential gain control coefficient; e (t) is the output error of the control system.

The control system output error expression is defined as:

$$e(t)=x(t)-y(t) \quad (2)$$

In the above equation, e(t) is the input value minus the output value.

But ordinary pid algorithm has delay in the process of adjustment, for the sweeping robot need to quickly response feedback machine effect, so need to introduce fuzzy PID algorithm, fuzzy PID algorithm through fuzzy control rules output correction, real-time PID parameters to cater the demands of different error and error rate of PID parameter self-regulation. Therefore, the system performance of the controlled object will be improved, and the static performance will be more stable [7].

The fuzzy pid theory algorithm is presented as follows:

The error e range was assumed as [-30,30] and divided into six equal parts, namely [-30, -20], [-20, -10], [-10,0], [0,10], [10,20], [20,30]. Then, -30, -20, -10,0,10,20,30 are represented by NB, NM, NS, ZO, PS, PM, and PB (N: negative; P: positive; S: small; M: middle; B: big; Z: zero;)

After determining the error range, we need to determine the membership function. For the simple calculation, we use the triangle membership function, as shown in the figure 1,

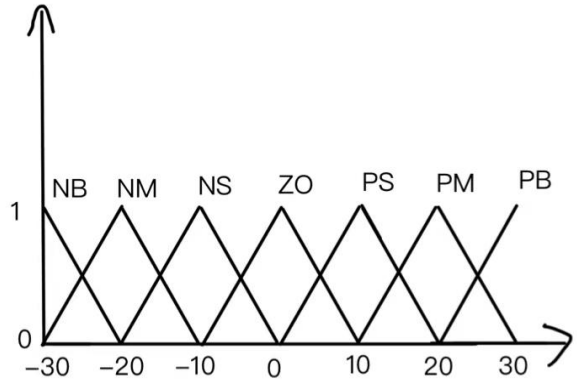


Figure 1. The triangle membership function (Photo credit: Original).

The value domain of membership is [0,1], assuming that the error e is 16.7, as shown in Fig 2.

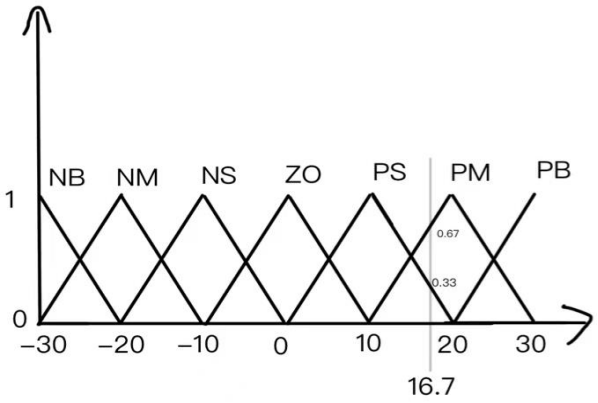


Figure 2. The value of e in function (Photo credit: Original).

The probability that PS occurs is 0.33, while PM occurs with a probability of 0.67. The subsequent step involves fuzzy reasoning, which relies on the membership degree of e relative to the rate of change, de/dt.

The fuzzy PID inference tables are utilized for this process. Currently, e is at 16.7, and it is assumed that de/dt is -3200, a value within the range of [-3600, 3600]. At this juncture, the membership value for blurred e is 0.33 for PS and 0.67 for PM. Concurrently, the membership values for de/dt are 0.67 for NB and 0.33 for NM. Subsequently, the membership pairs for e and de/dt are methodically calculated to facilitate the fuzzy reasoning process.

ΔKp: 0.33*0.67=0.2211(PS)
0.33*0.33=0.1089(PS)
0.67*0.67=0.4489(PS)
0.67*0.33=0.2211(ZO)
ΔKi: 0.33*0.67=0.2211(NM)
0.33*0.33=0.1089(NS)
0.67*0.67=0.4489(ZO)
0.67*0.33=0.2211(ZO)
ΔKd: 0.33*0.67=0.2211(ZO)
0.33*0.33=0.1089(ZO)
0.67*0.67=0.4489(PB)
0.67*0.33=0.2211(NS)

Integration above formula is available:

The membership degree of the Kp is 0.7789(PS), 0.2211(ZO).

The membership degree of the Ki is 0.67(ZO), 0.2211(NM), 0.1089(NS).

The membership degree of the Kd is 0.4489 (PB), 0.33(ZO), 0.2211(NS).

Finally, it needs to deblur and calculate the specific value of Δ PID in each membership degree.

E(Kp)=0.7789*10+0.2211*0=7.789

E(Ki)=0.67*0+0.2211*(-20) +0.1089*(-10) =-5.511

E(Kd)=0.33*0+0.4489*30+0.2211*(-10) =11.256

The calculated Δ pid value obtained above cannot be directly used as a systematic regulation, but the specific range of Kp, Ki and Kd need to be mapped to the interval as the regulation value.

Through the experience summary of multiple operations, the following relationship between the deviation e and the three parameters of the PID regulator, Kp, Ki and Kd, are summarized from the theoretical analysis.

When | e (t) | is large, a large Kp can reduce the time constant and damping coefficient of the system. But it cannot be too large, otherwise it will lead to system instability. In order to avoid uncontrollable situations outside the allowable range at the beginning, a small Kd should be taken to speed up the system response, and to avoid large overshoot, the integral action can be directly ignored, take Ki=0.

When | e (t) | in medium hours, should take a smaller Kp, make the system response slightly smaller; the accuracy of Kd value of the response speed of the system, debugging can slightly increase Ki, let the overall steady-state error of the system is smaller.

When | e (t) | is small, in order to make the system has good steady state performance, the larger Kp, Ki and Kd; in order to avoid the system oscillation in equilibrium point, we can use the characteristics that have ability to anticipate deviation trends of Kd to take the appropriate value.

Fuzzy PID is specifically applied to the configuration of the sweeping robot control system

In the Automatic central control system of the robot, the input value usually selects a certain data measured by the sensor, such as distance, angular speed, etc. A single input through PID correction output is not very good with other parameters. For example, when setting the route, an object suddenly blocks the route. If it is avoided by emergency stop or large Angle turn, it may cause bruises on the ground or have no time to avoid the object. However, the ordinary PID adjustment parameter needs multiple parameter feedback for the sudden increase of the error e (t) before the new adjustment configuration. Therefore, if you choose the multi-channel input to configure the fuzzy PID parameters, the real-time data of several sensors can be adjusted synchronously to achieve the rapid response to emergencies.

Here, take the distance sensor and inertial measurement sensor as an example. The output of the two are respectively the current length between the sweeping robot and the destination object and the real-time angular momentum of the sweeping robot. We blur the two parameters after weighted coupling, and the new blur parameters can be obtained.

The safety distance of the sweeping robot in the working path is set to 26 cm, that is, the speed is adjusted when the obstacle distance is less than 26 cm.

When the angular velocity of α detected a deviation of 16.7, i. e., an obstacle at 9.3 cm.

$$e(t)=16.7 \tag{3}$$

$$\omega=\alpha \tag{4}$$

Add the weight value of q according to the size of the angular velocity. The larger the angular velocity is set here, the smaller the degree of adjustment required, that is, the larger the vertical component speed of the object, the smaller the weight ratio of the angular velocity.

$$\omega 1=q*\alpha(-0.1<q<0.1) \tag{5}$$

$$e1(t)=e(t)+\omega 1 \tag{6}$$

The new error e1 (t) is substituted for fuzzy inference calculation. Here, we take ω equal to 0.05 and 0.5, respectively, to simulate the obstacles in front of the sweeping robot when turning at a large Angle and obstacles in front when running in a straight line. Assuming de / dt is-3200 (of range [-3600,3600]), the membership of de / dt would be 0.67 (NB) and 0.33 (NM).

$$\begin{gathered} e2(t)=16.75 \\ PM=0.675，PS=0.325 \\ e3(t)=17.2 \\ PM=0.72，PS=0.28 \end{gathered} \tag{7}$$

It can be obtained by querying:
e2(t)
The membership degree of the Kp is 0.77725(PS), 0.22275(ZO)
The membership degree of the Ki is 0.675(ZO), 0.21775(NM), 0.10725(NS)
The membership degree of the Kd is 0.45225 (PB), 0.325(ZO), 0.22275(NS)
e3(t)
The membership degree of the Kp is 0.7624(PS), 0.2376(ZO)
The membership degree of the Ki is 0.72(ZO), 0.1876(NM), 0.0924(NS)
The membership degree of the Kd is 0.4824 (PB), 0.28(ZO), 0.2376(NS)
Finally, the specific value of Δ PID that needs to be changed is obtained
e2(t)
e(Kp)=0.77725*10+0.22275*0=7.7725
e(Ki)=0.67*0+0.21775*(-20) +0.10725*(-10) =-5.4275
e(Kd)=0.325*0+0.45225*30+0.22275*(-10) =11.34
e3(t)
e(Kp)=0.7624*10+0.2376*0=7.624
e(Ki)=0.72*0+0.1876*(-20) +0.0924*(-10) =-4.676
e(Kd)=0.28*0+0.4824*30+0.2376*(-10) =12.096

Compared with the above two groups of different Δ PID adjustment value can be found in the same distance under the condition of different angular speed of PID after the weighted adjustment direction, the fuzzy PID parameter calculation results show that the steady state error needs longer balance, but also reduces the value of the steady state error, compared with the angular speed is small when fuzzy PID parameters shows that its dynamic performance need to adjust in time, namely reduce the proportion of overshoot more.

Therefore, if we choose the appropriate number of sensor input channels to establish a certain proportion of weighted fuzzy PID setting or segmented fuzzy PID setting, we can finally get more rapid system response and more stable system final state.

3. Existing Problems and Challenges

Although the comprehensive parameters of fuzzy PID in the case of multi-channel are calculated through the weighted parameter of the sensor, which makes some optimization for the sweeping robot in the path algorithm, it is not enough to only use the fuzzy PID to modulate the steering and velocity of the whole system on account of the actual situation. Most sweeping robots are two-degree of freedom robots. Based on the fuzzy PID, they can continue to optimize its algorithm according to the posture of the robot, such as designing and improving the particle swarm algorithm and optimizing the fuzzy PID controller. In the particle swarm optimization algorithm, the learning factor can affect the learning ability of the particle. If the learning factor is not selected properly, the learning speed between the particles is slower, and the optimization ability of the particle population is reduced, so the learning factor is improved as follows:

$$c_1=c_2=c_{min}+\frac{c_{max}-c_{min}}{T}\times \mathrm{t} \tag{8}$$

Then the particle swarm optimized algorithm is added to the fuzzy PID.

The resulting Δ PID parameter adjustment makes the system have faster corresponding speed and smaller steady-state error, which is more suitable for the pose adjustment of the two-DOF robot [8].

Adding more accurate sensors is also the key to obstacle avoidance. In order to realize the efficient navigation and obstacle avoidance ability of the sweeping robot, some studies combine the visual sensor to analyze the color, texture and shape characteristics in the image to identify the possible obstacles. By emitting the laser beam, the laser sensor can obtain information such as the distance and height of the obstacle. Using the laser scanning data, you can generate a map of the environment of the robot, and then determine whether the robot will collide with an obstacle by comparing it with the map. The ultrasonic sensor emits an ultrasonic signal and calculates the distance from the obstacle by receiving the echo signal. By setting the appropriate threshold value, the robot can effectively detect and avoid the obstacles in close proximity [9].

At the same time, the multi-channel sensor input will also make the system become more complex. With the miniaturization of the sweeping robot, lightweight, this is undoubtedly one of the problems that need to be solved [10].

The weighting parameter given in this article is a simple linear relationship, but in fact, the distance and angular velocity are more non-linear for the current operation of the sweeping robot, so the relationship function of the two weights needs to be determined in more thorough study.

4. Conclusion

This study meticulously explores the integration of fuzzy PID control with multi-input weighting for optimizing the path planning of household sweeping robots. It uncovers nuanced distinctions in the directional adjustments of fuzzy PID parameters contingent on weighted parameters, highlighting a sophisticated approach to adaptive control systems in robotics. By introducing external interference scenarios into the simulation, the necessity for dynamic adjustment of motion parameters becomes evident, advocating for a more responsive and adaptive control strategy. The research underscores the importance of synchronizing robot motion parameters with environmental variations to derive optimal path solutions. This integration of fuzzy logic with PID control fosters enhanced adaptability and precision in navigation tasks, a crucial advancement for robotic applications in cluttered and dynamic household environments. The findings from this investigation are significant, as they offer a robust framework for improving the efficiency and effectiveness of robotic cleaning devices, thereby enhancing user convenience and advancing the practical deployment of autonomous robots in everyday settings. Moreover, the implications of this research extend beyond mere technical enhancements. By improving the operational efficiency of household robots, this study contributes to the broader objective of automating domestic chores, freeing up human time for more valuable activities. The potential for increased adoption of such technology promises significant societal impacts, including shifts in lifestyle and further integration of smart technology in home management. Thus, the successful implementation of fuzzy PID control in robotic path optimization not only marks a technological advancement but also catalyzes a transformative shift in household management practices.

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