A Novel Tracking Mobile Robot System Based on Magnetic Navigation and Fuzzy PID Control

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Abstract
Based on magnetic navigation, a novel tracking mobile robot system is developed for unmanned vehicle applications. The system is mainly composed of four modules, namely detection, driving, control, and communication. The control module will analyse signals collected by the detection module, while the driving module controls the direction of the front wheels and the speed of the rear wheels. The system is able to achieve effective electromagnetic signal data collection using a newly designed I-inductor and the packaged data is then transmitted to controller through a serial to Bluetooth wireless module. The mobile robot speed is regulated by a closed-loop controller which can quickly transmit the data collected by the encoder to the controller, and a fuzzy PID controller is used to effectively adjust the speed of the mobile robot tracking. The experimental results show that the developed mobile robot can rapidly track the designed trajectory.

Key words: Magnetic Navigation, Fuzzy PID Control, Mobile Robot, Wireless Communication.

1. INTRODUCTION
With the rapid development of unmanned driving technologies, unmanned vehicles have been widely used to solve practical problems (Kuwata and Teo, 2009; Broggi and Buzzoni, 2013; Fagnat and Kochelman, 2015; Gordon and Lidberg, 2015). Unmanned intelligent mobile vehicles are a class of mobile robots that are featured by a comprehensive set of functions, including detection, identification, transmission, judgment, decision, optimization, control, feedback, and error correction, etc. It integrates embedded technology, sensor technology, electronics appliances, path planning, artificial intelligence, automatic control and other technologies. Unmanned intelligent mobile vehicles have been widely used in transportation, anti-terrorism, nuclear power plant maintenance, and unknown area exploitation transportation, etc.

Unmanned technology has been investigated since 1980s (Vandapel and Donamukkala, 2006; Loch and Wallar, 1989), the focus has then been gradually shifted auxiliary civilian vehicle driving in highway due to the limitations and complexity of unmanned technologies. For example, Toyota Company designed an unmanned driving system in 2000, which is mainly used for road guidance, motorcade driving, preventing the car crash, and operation management and so on. Mounted in the front of the car chassis, a magnetic sensor is used to navigate and control the travel of vehicles following the permanent magnet buried in the middle of the road. Representative research projects in the Europe include the CyberCars and CyberMove projects of the Fifth Framework and the CyberCars-2 project of the Sixth Framework.

A survey of the state of art development in autonomous vehicles, including upcoming technical challenges and opportunities is given in (Campbell and Egerstedt, 2010). An algorithm for automatic guided vehicle based on machine vision and Dead reckoning (DR) was designed which can efficiently improve the position precision
An adaptive fuzzy PID controller is designed to relate the trajectory to the joint angular parameters of the end-effector on a robot (Tao and Zheng, 2015). A fuzzy PID control algorithm is developed for an inspection robot navigation system, and the simulation shows that the algorithm provides better operational stability (Li and Cai, 2015).

Aiming to address problems affecting the speed and accuracy of mobile robots, we propose a novel tracking mobile robot system based on the magnetic navigation and fuzzy PID control. Section 2 introduces the system configuration which includes control, sensor, power, signal amplification, motor drive and wireless Bluetooth modules. In Section 3, the focus is on the software design of the control system. Section 4 presents the controller design, including a PI control and a fuzzy PID control. Experimental results are presented in Section 5, demonstrating the effectiveness of the developed system. Finally, conclusions are drawn and future work is also discussed.

2. SYSTEM CONFIGURATIONS

To achieve autonomous navigation of mobile robots, identification of the road conditions on a special runway and control of the speed are achieved through the integration of all modules. The system developed mainly comprises a control module, a sensor module, a power module, a signal amplification module, a motor drive module and a wireless Bluetooth module.

The system detects the pathway conditions using a sensor made of a forward l-inductance circuit. The detected signal is then amplified and transmitted to the controller by an AD channel. A main controller chip will control the motor drive module by sending commands after the data is processed. The motor drive module includes full a bridge circuit which consists of two BTS7960. An PWM pulse is used to control the motor speed, and a common IO is used to control the forward/reverse movement. At the same time, during the debugging stage, the signals will be detected by the mobile robot and transmitted to the controller by the Bluetooth module. The received data is then displayed for monitoring the debugging process and the mobile robot movement. The overall system block diagram is illustrated in Figure 1.

![Figure 1. Overall system block diagram](image)

2.1. Hardware Design

The mobile robot control system is made of the main controller MK60DN512, forward-looking sensors, servo-driven, encoder circuit, and wireless Bluetooth module, as shown in Figure 2. MK60DN512 is a Kinetis series microcontroller from Freescale and can meet the technical specifications of the mobile robot with rich resources.

![Figure 2. The block diagram of the mobile robot control hardware](image)
There is a higher demand on the computing power and running speed for the mobile robot to run in the prescribed specific route rapidly and stably. In this paper, the mobile robot needs three-way PWM at the same time which requires the microcontroller to have a higher frequency and at least three-way PWM functionality. Furthermore, a variety of sensors and wireless Bluetooth devices require the use of multi-channel I/O ports, which demands the microcontroller to have a good extension capacity.

2.2. Design of the Sensor Module

The sensor module consists of forward-looking inductive sensors and encoders. In order to detect the alternating magnetic field of the wire, forward-looking sensors detect the road information using combinations of sensor signals with the I-inductance. The encoder is used to translate the real-time speed signal of the tracking mobile robot and send to the master controller which is mainly in charge of the speed PID adjustment (Li and Shu, 2015).

The principle of the magnetic navigation system is to detect the changes in the magnetic field using the I-inductance sensors, and determine the type of track according to the signal from the magnetic field. In formula (1), the induced electromotive force output voltage \( V_{\text{out}} \) in a single coil is an even function of position \( x \), it is clear that a single coil is unable to distinguish between the left and right information of the track and only reflects the magnitude of the absolute value \( x \) in the horizontal position.

\[
E_d = E_1 - E_2 = \frac{h}{h^2 + x^2} - \frac{h}{h^2 + (x-L)^2} \tag{1}
\]

Suppose \( L=30\text{cm} \), the difference \( E_d \) of two coil electromotive forces can be calculated, as shown in Figure 3.

Figure 3. The relationship between the horizontal displacement and the voltage difference of two horizontal coils

As shown in Figure 3 that within the horizontal displacement of 0–30cm, the relationship between the electromotive force difference \( E_d \) and the displacement \( x \) is a monotonic function, which can help to control the steering of the mobile robot by a negative feedback, thus ensuring that the center position of the two coils is always along the centerline. The position detection range and the magnitude difference of the induced electromotive forces can be altered by changing the coil height \( h \) and the distance \( L \) between the two coils.

Figure 4. The scheme relative to the track in the forward-looking inductive sensor

A single pair of transverse inductors is difficult to distinguish between different track types. Thus, in the prospective left and right sides of the track, 6 inductance sensors, including two in parallel to the track, two in perpendicular to the track, and two with the track pitch angle of 10 degrees are adopted, as shown in Figure 4.

The advantage of this eight-character sensor scheme is that it captures the difference in the induced electromotive forces between the three groups of sensors which vary greatly, irrespective of the type of track in which the tracking mobile robot is located. The change to the electromotive force of the eight-character inductor sensor scheme is more obvious than that of the X-axis the mobile robot turns. This sensor scheme offers a great capability of detecting the type of track and calculating the deviations.

2.3. Motor Driving Module

The performance of the mobile robot highly depends on the motor so that it can achieve two-way rotation with desirable speed. Popular motor driving chip ULN2003 can only drive 4-phase stepper motor which does not
 meet the system design requirements. The motor control module LM298 can provide two-way load current which is suitable for driving two-phase or four-phase stepper motors. In addition, it can drive two ordinary brush DC motors, but its cooling function has not been effectively resolved when it uses LM298 as the driving circuit.

Given the above considerations, a bridge-driven circuit together with the motor driving chip BTS7960 is used as a motor driving module for the designed system, with this system, a PWM pulse is used to control the motor speed, and a common IO is used to control the positive reverse move.

2.4. Signal Amplifier Driver Module

Tracking mobile robot achieves navigation through the induction current signals from the magnetic field, and the selection of the inductance is crucial. In order to increase the amplitude of the signal output produced by the resonance, two issues need to be taken into account. First, to increase the strength of the output signal, the output resistance \( R_0 \) needs to be sufficiently large. Because the signal source on the track output has a frequency of 20 KHz, in order to match the desired output frequency, the greater the inductance is induced, the greater the inductor impedance becomes. To maximize the resonance attenuation around the vicinity of 20 KHz to achieve a proper frequency selection, the optimal inductance and capacitance are given as 10mH and 6.3nF respectively.

The 20 KHz signal can be effectively picked up by an LC detection circuit, as the data accuracy requirement for a line-tracking mobile robot is very high, the detection signal needs to be amplified in order to increase the measurement accuracy. As the output of the inductor is a sinusoidal AC signal, it has to be amplified and then converted to a DC signal. To achieve this, the amplifier chip LMV852MM is used in combination with a voltage detection circuit to obtain smooth DC voltage signals.

2.5. Design of Wireless Bluetooth Transmission Module

The track signals are collected by the inductance sensors of the mobile robot, which are fed back in real-time through the encoder, so each changed curve of the track will be recognised in real-time, leading to that the adjustment of the speed PID controller via different tuning algorithms. In the meantime, the real-time signals can be used to validate whether the sensors of the tracking mobile robot work properly. To achieve these functionalities, effective storage and retrieval of data in real-time along the entire mobile robot testing process becomes important.

In the designed system, the main controller and the Bluetooth module are connected through a serial port. The PC-side wireless Bluetooth module is connected to a USB interface through a USB-TTL converter. Car Bluetooth as the host sends the data detected by the sensor, the PC side in a slave mode receives data and the data displayed on the host computer.

3. SOFTWARE DESIGN

The software of the mobile robot has two routines, namely main routine and sub-routines. The main thread drives the main controller to execute the functions required by slave threads, thus help to complete the whole functionality of the mobile robot system.

![Figure 5. The flow chart of system software](image-url)
3.1. The Software Design

The main controller and the sensor module work simultaneously after the system is powered on. The main controller first initializes three timers. A timer can achieve 1ms interrupt used to generate the system basic clock. The other two can produce 50HZ and 100HZ PWM pulses used to control the servo rudder and DC motor. Then the system main loop starts, which first implements system protection procedures to detect whether the system and the electromagnetic signals are normal. It will continue the implementation of the master program if the detection is normal, otherwise all the output is zero, and the mobile robot is in a quiescent state. The master program processes the sensor data when the system is in normal state, and determines the type of the runway through data fitting to control the PWM output, and determines the servo rudder angle and DC motor speed.

In the execution of the above main routine, the system will also perform the other four sub-routines. It mainly includes speed control, servo rudder control, wireless Bluetooth transmission, and deviation data fitting, as shown in Figure 6.

![Figure 6. The subroutine flow chart with error fitting of the mobile robot](image)

The process of data fitting sub-routine of the mobile robot to calculate the difference between the position of the runway and the centre of the runway using the difference ratio and algorithm based on the data sent from the prospective sensor. The deviation data is passed to the speed control subroutine and the servo controller subroutine to identify the runway.

The motor control sub-routine runs the complete PID closed-loop control. The encoder measures the speed of the mobile robot and sends to the PID regulator. The main controller determines the speed of the mobile robot by judging the type of the road and stores in the buffer area. The PID controller reads the speed setting from the buffer and outputs the PWM pulse signal. The speed control of the motor is achieved by adjusting the duty cycle of the PWM pulse such that the mobile robot is set at different speed.

The servo control subroutine of the mobile robot runs an incremental PID control. The second deviation value and the first deviation value are saved in the buffer area. The PID controller reads the offset value from the buffer area and outputs the PWM pulse. The turning radius of the mobile robot can be obtained through the data fitting of sensor data from the mobile robot, which controls the angle and size of the steering servo of the mobile robot.

In the communication sub-routine, the main controller reads the transmission data from the sensor. The Bluetooth module of the PC side receives data from the Bluetooth module located at the car, and it will be displayed at the host computer.

3.2. Speed Detection

The counting of the encoder is achieved by the fixed time module (FTM) function of the main controller. The actual travelled distance of the mobile robot is calculated as the count number N multiplied by the distance 22/500 in one pulse. The sampling period of the main controller for one pulse is 10s. The actual speed of the mobile robot is calculated from the traveling distance in 10ms.

To count the pulses of the encoder, the system needs to configure the external pulse counting function of the timer FTM to calculate the actual distance and speed of the mobile robot.
4. CONTROL ALGORITHM DESIGN

The control system first calculates the actual deviation between the trajectory of the mobile robot and the desired track using the difference ratio and algorithm, and then uses the fuzzy PI control algorithm to move the mobile robot along the desired trajectory, further improving the system tracking stability of the mobile robot (Rocca and Manica, 2009).

4.1. Deviation Fitting using Difference Ratio and Algorithm

The system has improved the difference ratio and algorithm which has a denominator part and a numerator part. In the denominator part, the same group is multiplied by a relative scale factor between the three groups of sensors, and then the three sets of data are added together to work out the denominator. The numerator part is the difference of the induced electromotive force of each group of inductors. Division of the numerator part by the denominator part leads to three sets of deviations in different directions, including Errx in the X direction, Erry in the Y direction and Errxy in the XY direction. The actual deviation of the mobile robot on the desired track is then calculated by multiplying the deviations in different directions with different proportions and finally adding up as shown in (2) to (6).

\[ \text{dum} = n_1 \cdot (AD_{x1} + AD_{y2}) + n_2 \cdot (AD_{x1} + AD_{y2}) + n_3 \cdot (AD_{y1} + AD_{y2}) \]  

\[ E_{rx} = n \cdot (AD_{x1} - AD_{x2}) / \text{dum} \]  

\[ E_{ry} = n \cdot (AD_{y1} - AD_{y2}) / \text{dum} \]  

\[ E_{rxy} = n \cdot (AD_{y1} - AD_{y2}) / \text{dum} \]  

\[ E_{rx} = n_1 \cdot E_{rx} + n_2 \cdot E_{ry} + n_3 \cdot E_{rxy} \]  

From equations (2) to (6), AD represents the electromotive force of a single inductor, n is the proportional coefficient, and Err is the actual deviation of the mobile robot in the track. Compared with traditional difference ratio and algorithm, the system uses an improved algorithm to reduce the decay rate of the numerator, while decay rate of the denominator remains unchanged. The disadvantage of the traditional difference ratio and algorithm, which may cause significant calculation deviation as shown in Figure 7, is thus avoided.

![Figure 7. The curve of deviation after fitting.](image)

As shown in Figure 7, the mobile robot is slowly moved from the leftmost end to the rightmost at end of the track, resulting deviations from -90 to 90. It is clear that the deviation is continuous. It is clear that the deviation calculation is a key to ensure a continuous tracking angle of the mobile robot, and it is a prerequisite to achieve the acceleration of the mobile robot.

4.2. Speed Control of The Mobile Robot

The system uses a fuzzy PI controller to control the actual speed of the mobile robot. The motor output PWM is determined by the deviation of the actual speed feedback from the encoder and the given speed, together with the deviation accumulation. The following speed control algorithms have been tested and the fuzzy PI controller is finally chosen to control the speed.

1. The speed control under the PI controller

Considering that bang-bang control is difficult to achieve desirable mobile robot speed, the traditional PI controller is used. Because the differential term in the traditional PID is to enhance the response speed, but a general PWM inverter mainly provides the velocity modulation, and does not require a very high response speed.
It is enough to improve the response speed using the proportion component. Further, the differential component is easy to cause early saturation and increase risk of system instability, therefore the differential term is not used to control the speed of the trajectory mobile.

The tuning of the PI controller works like the following. First, a purely proportional regulation is applied, and then the proportional gain starts from 0 and is increased gradually until the oscillation of the system occurs. Conversely, the proportional gain P is gradually reduced until the oscillation of the system disappeared. The proportional gain P is set to a value between 60% to 70% of the current value. At this point the integral term I is then added, so that the integral parameter is gradually increased until the frequency of the system oscillation is reduced, and oscillation amplitude is becoming very small at last. At this point it adjusts the scale factor such that the system tends to be as stable as possible. This approach however is slow to adjust for a lag system and thus takes time to stabilize.

2. The fuzzy controller

The fuzzy control system is based on the fuzzy set theory, knowledge representation of fuzzy linguistic form and fuzzy logic reasoning. It mimics human’s fuzzy thinking mode and can be used to control a complex process. The fuzzy control process is shown in Figure 8.

![Figure 8. Fuzzy control process.](image)

The fuzzy PI controller is an adaptive control system which is based on the conventional PI control and the fuzzy rules which is used to adjust the PI parameters. The error e and error rate ec are taken as input parameters for the fuzzy rules to adjust the parameters for different e and ec. The combination of fuzzy system and PI controller can not only retain the flexibility and adaptability of the fuzzy control, but also achieve high control accuracy due to the PI control. The fuzzy PI controller therefore has the potential to deliver good control performance for the relatively complex mobile robot tracking system [Chwa, 2015].

3. Fuzzy PI controller based speed control

After a comparative study, a fuzzy PI controller is finally used to control the speed of the tracking robot, where the parameters of the PI controller are tuned by the fuzzy system. The following steps are adopted to determine the PI parameters using the fuzzy system.

(1) To determine input and output of the fuzzy system

The fuzzy inputs include error e and error rate ec of the DC which are obtained through the encoder data acquisition, \(K_p\) and \(K_i\) are the outputs of the fuzzy system.

(2) Fuzzification of input and output variables

To achieve high precision of fuzzy control, the variable quantization level has to be high, yet it imposes greater operating pressure on the main controller. In this system, the quantization scale of the two linguistic variables is set to 7, and the fuzzy sets for error e and error rate ec are given as \{ -3, -2, -1, 0, 1, 2, 3 \}. The fuzzy subsets represent NB (negative big), NM (negative middle), NS (negative small), ZO (zero), PS (positive small), PM (positive middle) and PB (positive big). The input and output variables are fuzzified using the common triangular membership function for which the output is single valued. The membership functions in each fuzzy subset are tuned based on the experimental results.

(3) Fuzzy rules

The fuzzy rules define the relation between the two inputs, namely the angular velocity error e as well as the error rate ec of the DC motor, with the two output parameters, namely the proportional gain \(K_p\) as well as the integral gain \(K_i\) in the PI controller. The rules are determined by expert experience and experiments. If e is small and ec is large and the two signs are the same, it indicates that the track type has a curve ahead. In this case, the mobile robot is required to move inward. Therefore, large \(K_p\) and large \(K_i\) should be used in program.

Likewise, if both e and ec are large and both directions are the same, it indicates that the track ahead is not a very steep bend. The program should use the medium \(K_p\) and small \(K_i\) to enable the robot move along the bend smoothly. If e and ec are very large and both directions are the same, it indicates that the mobile robot is running on a sharp bend. Then, both large \(K_p\) and \(K_i\) are needed in order to enable the robot travel through the corner safely. It is clear that the fuzzy rules are defined according to the track conditions of the mobile robot [Castillo and Melin, 2012]. The fuzzy rules of \(K_p\) and \(K_i\) are shown in Table 1 and Table 2 respectively.
The outputs from the fuzzy rules in Table 1 and Table 2 need to be aggregated to produce a crisp value for the two control parameters $K_p$ and $K_i$ for the mobile robot. This system uses the center of gravity method to produce crisp values. During the movement of the mobile robot, the control system constantly queries the fuzzy rules based on the readings of the error $e$ and error change rate $ec$. According to (5) and (6), the PI controller is parameterized. The parameter tuning of $K_p$ and $K_i$ are as follows:

$$
\begin{align*}
K_p &= K_p' + \Delta K_p \\
K_i &= K_i' + \Delta K_i 
\end{align*}
$$

In Equation (7), $K_p$ and $K_i$ are the updated parameters of the PI controller, $K_p'$ and $K_i'$ are current values for two control parameters. In practice, the system continuously detects the robot speed from the encoder. The program then calculates the error $e$ and error change rate $ec$ from the acquired velocity value, and then obtains $E$ and $EC$ by fuzzification of the error and error change rate. Then the amount of adjustment $\Delta K_p$ and $\Delta K_i$ are updated by querying the fuzzy table.

![Figure 9](image-url)
5 EXPERIMENTAL RESULTS AND TESTING

5.1. The Result of PI Controller

The speed adjustment with PI controller is shown in Figure 9.

In Figure 9, the blue line is the desired speed, and the red one illustrates the actual speed of the mobile robot. Under the PI controller, the system response speed initially reaches the desired value, but it is difficult to eliminate the steady-state error, no matter how the proportional term P is adjusted. For a complex tracking system, a fixed set of PI parameters is difficult to adapt to different tracking situations. During the movement of the mobile robot, the adjustment of the PI parameter needs to be different depending on the track conditions from the straight path to the curved path. For example, moving from a straight track into a bend of 120 radians, the proportional item P relative has to decrease significantly.

5.2. The Result of Fuzzy PI Controller

The two controller designs are implemented in the robot and tested under different track conditions. The resulting velocity curve meets the tracking requirements of the mobile robot as shown in Figure 10.

![Figure 10. The speed curve under the fuzzy PI controller.](image)

It is shown from Figure 10 that the actual speed of the mobile robot tracks well with the desired velocity curve, and the system steady-state error is largely eliminated. The adjustment and control of the robot speed using the fuzzy PI controller is shown to be superior to the traditional PI controller as it is more adaptive to the environmental changes. The intelligent tuning of the control parameters in the fuzzy controller makes the system more adaptive for complex tracking environment.

5.3. Effectiveness Analysis on the Inductance Scheme

The mobile robot moves following a set route by the means of magnetic field navigation. The different track type will result in different track magnetic field strength. For example, in a cross shaped track, the magnetic field strength highly depends on the placement of the inductance circuit. While for two parallel sections closing to each other, and currents in the same direction will strengthen the magnetic field, otherwise, the magnetic field strength becomes weakened if the current directions are opposite. It is therefore important to design the inductive placement scheme that effectively differentiates all road information. The designed mobile robot is shown in Figure 11.

![Figure 11. The object of the mobile robot.](image)

6. CONCLUSION AND FUTURE WORK

In this paper, we have shown that good mobile robot tracking performance can be achieved using the magnetic field navigation and fuzzy PID control algorithm. A wireless transmission module has been designed to
transmit the information of the mobile robot to a PC terminal, which completes data acquisition. The PID parameters are tuned using some auxiliary tools, and the collected data is passed to the control software to tune the PID parameters. Experimental results show that when the speed of the mobile robot is greater than 3m/s, for moving every 4 cm it needs to transfer the data, which imposes constraints on the real-time data analysis. It is clear that the data transmission scheme needs to be further optimized, and techniques such as the secondary cache can be implemented to improve the data transmission efficiency and completeness.

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