Design of temperature control system for infant radiant warmer based on Kalman filter-fuzzy PID

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Abstract. In order to improve the dynamic and static performance of the temperature control system of the baby radiant warmer, a Kalman filter-fuzzy PID (KFPID) algorithm is proposed on the basis of the ordinary incremental PID control algorithm. The system uses STM32 as the main controller. The temperature data is collected by the TLV2548 analog-to-digital conversion chip, and the feedback data is filtered by Kalman filter, and the bed surface of the warming table is controlled by the fuzzy PID control algorithm. After the simulation of Matlab, it can be seen that compared with the traditional PID temperature control algorithm, the KFPID algorithm has the characteristics of short adjustment time and almost zero overshoot, and the steady-state error is smaller when dealing with the same interference noise.

1. Introduction
Infant radiant warmer refers to a warm nursing device dedicated to newborns, premature infants, critically ill infants, and frail infants[1]. It is equipped with an infrared radiation device to provide a continuous heat preservation environment for babies by means of infrared radiation heating[2]. It can be seen that the stability of temperature control will be one of the important indicators to measure the performance of a warming station, so it is of great practical significance to design a set of temperature control algorithms with stable performance. At present, the temperature control algorithm used in common heating stations in our country mainly adopts the ordinary incremental PID algorithm. However, because the corresponding proportional coefficient, integral coefficient, and differential coefficient are fixed, it cannot be satisfied with the temperature control system of hysteresis and large inertia, such as radiant warmer[3]. For the control system whose mathematical model is difficult to determine, Zadeh[4] first proposed the related theory of fuzzy control in 1965. In 1974, Mamdani applied it to the control of boilers and steam engines successfully[5]. Although the fuzzy control algorithm can combine with the artificial experience to optimize the control system and has good robustness, its control accuracy is relatively low and there is a steady-state error.

In this paper, based on the ordinary incremental PID algorithm, Kalman filter[6] and fuzzy control technology are introduced, and a temperature control system based on the KFPID algorithm is designed. After simulation, it is found that compared with the ordinary PID temperature control algorithm, the designed algorithm has the characteristics of short adjustment time and better control quality. It has strong stability when dealing with external noise interference and can also be applied to other control systems of temperatures.
2. Overall design of temperature control system

The principle block diagram of the temperature control system is shown in Figure 1. Medical staff need to set the temperature in advance before using the radiant warmer. The microcontroller unit (MCU) will run the fuzzy PID control algorithm after receiving the input signal. The square wave of pulse width modulation (PWM) with adjustable duty cycle is calculated according to the difference between the set temperature and the actual temperature. The drive circuit controls the opening and closing of the solid-state relay, thereby controlling the heating of the infrared radiation head, so that the bed surface of the radiant warmer reaches the preset temperature. The skin temperature sensor with negative temperature coefficient converts the temperature signal into an analog signal through the temperature acquisition circuit. The analog conversion chip of TLV2548 converts the analog signal into the digital signal and then transmits it to the MCU. The program of temperature data conversion will convert the received digital quantity into the corresponding temperature value as well as change curve, and display it on the LCD, or upload the data to the PC through the RS232 serial port.

In addition to achieving the above-mentioned functions, the entire control system can also monitor the heating power of the radiant head in real time to determine whether the heating is abnormal. Once an abnormality is found, the LCD displays an alarm message, and simultaneously emits an audible and visual alarm. When the bed surface temperature exceeds 40 degrees Celsius, an over-temperature alarm will be issued. The temperature data will be saved to the FLASH memory chip every second for subsequent data analysis.

3. Design of fuzzy PID controller based on Kalman filter

Fuzzy PID control can dynamically adjust the proportional coefficient, differential coefficient and integral coefficient on the basis of PID control, it can also realize the online adjustment of PID parameters and obtain better dynamic and static performance[7]. The schematic diagram of fuzzy PID controller based on Kalman filter is shown in Figure 2.

\[ X(t) \] is the system input, \( Y(t) \) is the system output, and \( e \) is the temperature deviation. The fuzzy inference machine receives signals of deviation and deviation rate of change. The input is fuzzified, and then fuzzy inference is performed according to the rule base. After defuzzification, the \( \Delta k_p \), \( \Delta k_i \), and \( \Delta k_d \) variables are output respectively.

Since the radiant warmer is used in an open environment, it will inevitably be affected by the temperature fluctuation of the air conditioner. At the same time, considering the movement of people, there will be air circulation with the outside world, so interference noise will be introduced. However, the skin temperature sensor may also have errors due to the limitations of the manufacturing process, resulting in measurement noise, so a Kalman filter is designed here. The interference noise and measurement noise enter the Kalman filter, and the optimized temperature signal is transmitted to the fuzzy PID controller.
3.1. Kalman filter

Rudolph Emil Kalman gave the related theory of Kalman filter of discrete time system as early as 1960[8]. Kalman filter can predict effectively in the system with uncertain interference, and it occupies a small amount of memory, which is suitable for various complex environments. The purpose of Kalman filter is to minimize the estimated mean square value and reduce the interference of the system output signal by noise. In the filtering process, the estimated value is continuously corrected through the recursive algorithm, and finally the error mean square value is minimized. The process model and measurement model of the discrete system are as follows:

\[ x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \]  

\[ z_k = Hx_k + v_k \]  

Where \( x_k \) and \( x_{k-1} \) respectively represent the to-be-estimated quantities of the system at time \( k \) and time \( k-1 \), \( A \) is the state transition matrix, \( B \) is the gain matrix of the input control vector, \( u_{k-1} \) is the input control vector, and \( w_{k-1} \) is process noise, \( z_k \) is the measurement data obtained by the sensor, \( H \) is the conversion matrix from the state variable to the measurement, and \( v_k \) is the measurement noise.

Predict:

\[ \hat{x}_k^- = A\hat{x}_{k-1}^- + Bu_{k-1} \]  

\[ P_k^- = AP_{k-1}^-A^T + Q \]  

Update:

\[ K_k = P_k^-H^T\left(HP_k^-H^T + R\right)^{-1} \]  

\[ \hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-) \]  

\[ P_k = (I - K_kH)P_k^- \]  

Where \( \hat{x}_k^- \) represents the pre-estimated value at time \( k \), \( \hat{x}_k \) and \( \hat{x}_{k-1}^- \) represent the predicted value of the system at time \( k \) and \( k-1 \), \( Q \) is the process noise covariance, \( R \) is the measurement noise covariance, \( P_{k-1}^- \) and \( P_k^- \) represent the predicted value covariance at \( k-1 \) and \( k \), \( P_k^- \) represents the pre-estimated value covariance at \( k \), \( K_k \) is the Kalman filter coefficient.

In order to verify the noise suppression effect of the Kalman filter on the temperature measurement data, Matlab software is used for simulation, and the effect diagram is shown in Figure 3. Assuming that the ideal temperature rise curve is \( y = 20 + t \), the mean value of the simulated measurement noise is 0, the variance is 2, the blue line is the measured temperature value, and the black line is the curve.
after Kalman filter. It can be found that Kalman filter has a better suppression effect on measurement noise.

Figure 3. Temperature measurement-Kalman filter simulation diagram

3.2. Fuzzy PID control algorithm
The temperature deviation \( e \) and the deviation change rate \( ec \) can be obtained by comparing the collected filter data with the set temperature, which can be used as the input of the fuzzy PID controller. After fuzzification, fuzzy inference is carried out according to the formulated fuzzy rules, and finally the correction amount of the output PID parameters is obtained after defuzzification: \( \Delta k_p \), \( \Delta k_i \) and \( \Delta k_d \).

3.2.1. Fuzzy universe
Considering the range of temperature deviation \( e \) and deviation change rate \( ec \) under the actual working conditions of the baby radiant warmer, the basic domain of \( e \) is \([-30,30]\), the fuzzy domain is \([-6,6]\), and the basic domain and fuzzy domain of \( ec \) are both \([-3,3]\). The basic domains of the proportional coefficient change \( \Delta k_p \), the integral coefficient change \( \Delta k_i \), and the differential coefficient change \( \Delta k_d \) are \([-45,45]\), \([-0.8,0.8]\), \([-60,60]\), and the corresponding fuzzy domain values are the same as the basic domain. The fuzzy subsets of all variables are \{NB,NM,NS,ZO,PS,PM,PB\}, in which each element represents negative large, negative medium, negative small, zero, positive small, positive middle, and positive large.

3.2.2. Fuzzification
Converting a certain input quantity into a fuzzy quantity is called fuzzification, where the type of membership function is related to the stability and rapidity of temperature response. In order to ensure the accuracy of fuzzy inference without affecting the sensitivity of system control and reducing the amount of calculation, the triangular membership functions are used for both input and output variables.

3.2.3. Fuzzy rules and fuzzy reasoning
Combining expert experience and the heating characteristics of the radiant warmer, the fuzzy rule table as shown in Table 1 is obtained after simulation debugging.
Tab 1. The fuzzy control rule table of $\Delta k_p$, $\Delta k_i$, $\Delta k_d$

| $E$     | NB       | NM       | NS       | ZO       | PS       | PM       | PB       |
|---------|----------|----------|----------|----------|----------|----------|----------|
| EC      |          |          |          |          |          |          |          |
| NB      | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NM | ZO/ZO/PS |
| NM      | PM/NB/PM | PM/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NS | NS/ZO/PS |
| NS      | PM/NB/ZO | PM/NM/NS | PS/NS/NM | ZO/NS/NS | ZO/ZO/NS | NS/PS/NS | NS/PS/ZO |
| ZO      | PM/NM/PS | PM/NM/ZO | PS/ZO/NS | ZO/ZO/NS | ZO/ZO/NS | NS/PS/NS | NM/PS/ZO |
| PS      | PS/NS/PS | PS/NS/ZO | ZO/ZO/ZO | NS/PS/ZO | NS/PS/ZO | NM/PM/ZO | NM/PM/PS |
| PM      | ZO/NM/PB | ZO/NS/PS | NS/PS/PS | NS/PS/PS | NM/PM/PS | NM/PM/PS | NB/PB/PB |
| PB      | ZO/ZO/PB | ZO/ZO/PM | NM/PS/PM | NM/PM/PB | NM/PM/PS | NM/PM/PS | NB/PB/PB |

3.2.4. Defuzzification
The result of fuzzy inference is the fuzzy quantity, which cannot be directly used as the control quantity of the controlled object. Considering the amount of calculation and calculation accuracy, the weighted average method is used to resolve the fuzzy to obtain $\Delta k_p$, $\Delta k_i$ and $\Delta k_d$. The PID control parameters $k_p$, $k_i$ and $k_d$ can be obtained by formula (8).

$$\begin{align*}
    k_p &= k_{p0} + \Delta k_p \\
    k_i &= k_{i0} + \Delta k_i \\
    k_d &= k_{d0} + \Delta k_d
\end{align*}$$

Where $k_{p0}$, $k_{i0}$, and $k_{d0}$ are the initial proportional coefficient, integral coefficient and differential coefficient, respectively.

4. Simulation experiment
Matlab software is used to design the ordinary PID and KFPID algorithms. The initial temperature is set to 23℃, the target temperature is set to 37℃, the simulation time is 8000s, and the sampling time is 1s. Considering the interference noise and measurement noise in the real working environment of the radiant warmer, the same noise signal is applied to the two control algorithms respectively, and the response curve is shown in Figure 4.
The parameter comparison of the two different control algorithms is shown in Table 2. Combined with Figure 4, it can be found that compared with the ordinary PID algorithm, the KFPID algorithm has a smaller overshoot, a shorter adjustment time, and a smaller steady-state error against the same interference noise.

| Control algorithm | Rising Time/s | Overshoot/% | Adjustment time/s | Steady-state error/℃ |
|-------------------|---------------|-------------|-------------------|----------------------|
| PID               | 1143          | 4.5         | 4175              | 0.98                 |
| KFPID             | 1500          | 0.4         | 1590              | 0.18                 |

5. Conclusion

Based on the principle of Kalman filter and fuzzy control, this paper designs a set of temperature control system for infant radiant warmer controlled by KFPID algorithm. Through the comparison of simulation experiments, it is found that the control performance of KFPID algorithm is better than that of ordinary PID control algorithm. The main performance is that the convergence time is short, the overshoot is almost zero, and the effect of Kalman filter is significant when interfered with interference and measurement noise. The control algorithm has strong adaptability and provides a reference for the temperature control design of related baby care products.

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