International Journal of Control and Automation
Vol. 9, No. 9 (2016), pp.117-128
http//dx.doi.org/10.14257/ijca.2016.9.9.12

The Design and Implementation of an Intelligent Infusion System based on Fuzzy Control

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Abstract

In present medical practice, infusion is an important and widely adopted treatment method. During the infusion process, the dripping speed of infusion is a significant parameter. In this paper, an intelligent infusion system is introduced, which is provided with dripping speed remote setting and abnormal situation alarm function. Through the application of fuzzy-PID control with auto-adjusted factors, the control of dripping speed is achieved. ZigBee and Wi-Fi construct a wireless network, therefore medical staff can set the dripping speed by making use of mobile terminals and meanwhile, the dripping speed is displayed on mobile terminals for nurses' reference. The test results indicate the following characteristics of the intelligent infusion system, such as fast response and high accuracy. Besides, the results also prove that the intelligent infusion system achieves the objective of reducing medical staff's workload and improving patients' safety.

Keywords: *Intelligent infusion system; Fuzzy Control; PID Control*

1. Introduction

In recent years, clinical medicine has a rapid development. Meanwhile, hospitals have also strengthened the construction toward information, automation and intelligence. With the supports of government, medical equipment markets in China develop fast in the last few years. Although the market only shares 5% of the global market, the government demands a 25% share of the global medical equipment market in 2050.

In China, the current situation of the hospital is heavy workload on nurses, patients and medical staff. Based on experience and bare eyes, nurses adjust the infusion speed and, this infusion speed management method can result in disastrous medical accidents provided that the infusion speed is too low or too fast. On one hand, patients need relatives to accompany and this is a great burden to family members on work and life. On the other hand, neglects on patients can cause blood return and even life-threatening events. During the infusion, traditional infusion system cannot alarm when the following failures occurs, such as bubbles and obstructions, or cut the infusion pathway to prevent further damage. Fuzzy control refers to the application of the fuzzy theory in the control technology, during which language variables instead of mathematical variables are adopted. In addition, fuzzy control is appropriate for industrial processes without a mathematical model or hard to build a mathematical model. Moreover, variables in those processes tend to be non-linear variables. Fuzzy control is an efficient way to solve uncertain problems in non-leaner systems, which does not need a specific mathematical model. In the intelligent infusion system, the dripping speed control system is a non-leaner system. Therefore, the fuzzy control method can be applied in the intelligent infusion system, so as to achieve precise and accurate dripping speed control.

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ISSN: 2005-4297 IJCA

2. The Fuzzy Control Algorithm

As current fuzzy control algorithm tends to produce steady-state error, a adjusted fuzzy control algorithm must be adopted to diminish the error and achieve traumatic infusion dripping speed control.

2.1. The Conventional Fuzzy Control Algorithm

30 years ago, fuzzy control technology was born and the application reveals fast response, low overshoot and good robustness features of conventional fuzzy control system. However, the fuzzy control system has the problem of unstable steady state when related to complicated controlled objects. Conventional two-dimensional fuzzy controller is based on error input and error change rate. Therefore, the controller is generally believed to have fuzzy proportion - micro control function. Nevertheless, due to the lack of fuzzy integral function, the controller has difficulties in eliminating steady state errors and maintaining at high accuracy.

2.2. Fuzzy - PID Compound Controller

In order to improve the precision and track the performance of fuzzy controller, more language variables must be used in the controller. In the meantime, the number of rules and calculation amount are also increased significantly. In the rules of fuzzy control, the result is difficult. One way to solve this contradiction is to adopt different control methods in different theory domains. In order to improve the response speed of system and speed up the response process, the ration control is activated when the deviation is greater than a certain threshold; the system can switch to fuzzy-PID control when the deviation is below the threshold, so as to improve the system performance and reduce the overshoot during the response. The fuzzy-PID controller combines advantages of ratio controller and fuzzy controller, which compresses the theory domain of fuzzy control to a portion of overall theory domain and the change equals to the sections increased in the language variables. Therefore, accuracy and sensitivity are improved in the new controller.

However, fuzzy control has no integral operation and the control has limited processing ability on discrete data, whose control surface is ladder shape rather than a smooth surface. Therefore, steady-state error is inevitable in the control method, which may cause a small amplitude of oscillation near the equilibrium point. Furthermore, the effect of PID control is satisfying in small scale and its integral effect can eliminate the state error theoretically. In the next step, advantages of ration control and fuzzy control can be combined by a multimodal subsection control algorithm. The fuzzy-PID control method not only improves the system's response time, response accuracy and robustness, but also realize highly accurate fuzzy-PID control. In Figure 1, the structure of the control method is presented.

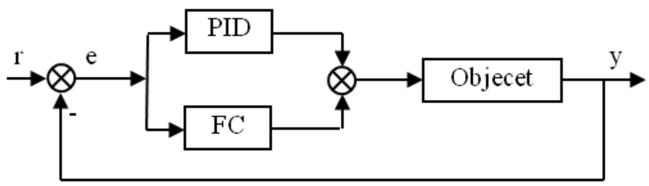

Figure 1. The Structure of the Fuzzy-PID Compound Controller

Assuming that EP is one threshold, the system adopts fuzzy control when E≥EP; while the system uses PID control when E<EZ.

In the system working session, the three kinds of control modes will never be mixed up and design and debugging of the three systems must be separately undertaken. In the control algorithm, the major problem appears in the selection of a proper control mode switch threshold. In the case that the threshold is too big, the system will enter ratio mode too early and the system respond time is increased with low overshoot. In the case that the threshold is too small, the system will possess a high overshoot near the switch point. Based on the following ideas, optimal switch point is selected: When the system changes from fuzzy mode to PID mode, the optimal point is where the language value equals to “zero” (ZE). When E=ZE, the system is under PID control mode and the PID algorithm is:

$$U_n = U_{n-1} + K_p (E_n - E_{n-1}) + K_i E_n \tag{1}$$

In (1), Kp is the ratio coefficient, Ki is the integral coefficient and U is the output control variable of PID.

In fuzzy control, when language variable equals to "zero" (ZE), the absolute error is not necessarily zero. As a matter of fact, the state performance of the system can be improved on this basis according to the absolute error and error change trend. When the absolute error is increasing, this integrator works as integral function, which however equals to a constant when the absolute error is decreasing. When E=0 or the integral is saturated, the integrator can reset automatically.

The simulation results demonstrate that comparing with conventional PID controller, the fuzzy-PID controller makes advances in anti-external disturbance, high robustness, low overshoot and fine dynamic characteristics. When compared to simple fuzzy control mode, the fuzzy-PID control mode is provided with good characteristics of accuracy and precision.

2.3. Fuzzy Control Mode with Auto-Adjusted Factors

With the increase of control sections, the above fuzzy-PID control mode brings the problem of large computing workload. In order to solve this problem, self-adjusting factors method is introduced to the fuzzy control system, which will reduce the workload of the fuzzy control system and thus optimization of the system performance is maintained.

Assume the error is E, the error change rate is EC, the theory domain of the control variable U is:

$$\{E\} = \{EC\} = \{U\} = \{-N, \cdots, -1, 0, 1, \cdots, N\} \tag{2}$$

Then the self-adjusted whole theory domain fuzzy control rule is:

$$\begin{cases} u = -< aE + (1-a)EC > \\ a = \dfrac{1}{N}(a_s - a_0)|E| + a_0 \end{cases} \tag{3}$$

In (3), $0 \le a_0 \le a_n \le 1, a \in [a_0, a_n]$.

The control rule in (3) has a characteristic that adjusted factor a changes in linear while the $|E|$ change in the range of a_0 and a_n.

The quantitive control method in (3) reflects the weighed effect of the auto-adjusted error on control results. Because of the auto-adjusting is on the whole error theory domain, the (3) is also called the quantitive fuzzy control rule with auto-adjusted factors on the whole theory domain. This fuzzy control method satisfies the needs of the intelligent infusion system in this paper.

2.4. The PID Control Algorithm

PID controller is a kind of regulator based on proportional, integral, derivative methods, it's the most widely used continuous system regulator. It has the characteristics of simple structure and easy setting. Through the using experience and theoretical analysis, the PID regulator can result in satisfied control effects on different control objects. In the fuzzy-PID controller, the PID control algorithm is:

$$u(t) = k_p[e(t) + \frac{1}{T_i}\int_0 e(t)dt + T_d \frac{de(t)}{d(t)}] \tag{4}$$

In (4), u(t) is the output of the regulator, e(t) is the deviation signal, e(t) equals to the subtraction of the setting value and the output, k_p is the proportional coefficient, T_i is the time integral coefficient, T_d is the time derivative coefficient.

The computer system is a kind of sampling control system, it can only can calculate the control variable based on the sampling time deviation, thus to achieve (4), the data must be discretized, and the differential equation in the continuous system must be replaced by partial difference equation.

The discretization of the continuous system can use the equation:

$$t = KT(K = 0,1,2,\cdots,n) \tag{5}$$

Integral with cumulative summation approximation:

$$\int_0 e(t)dt = \sum_{j=0}^{k} e(j)T = T\sum_{j=0}^{k} e(j) \tag{6}$$

Differential of the first-order approximation:

$$\frac{de(t)}{dt} \approx \frac{e(k) - e(k-1)}{T} \tag{7}$$

In (7), T is sampling period, e(k) is the deviation of number k sampling, e(k-1) is the deviation of the number k-1 sampling. Based on (6) and (7), (4) is changed to:

$$u(k) = K_P\{e(k) + \frac{T}{T_i}\sum_{J=0}^{k} e(j) + \frac{T_d}{T}[e(k) - e(k-1)]\} \tag{8}$$

If the sampling period T is small enough, (8) is proximate simulation of the PID algorithm. In real situation, every output is related to all the previous state, the calculation isn't efficient with (8), the deduction form of (8) is:

$$u(k) = u(k-1) + a_0 e(k) - a_1 e(k-1) + a_2 e(k-2) \tag{9}$$

In (9), $a_0 = k_p(1 + \frac{T}{T_i} + \frac{T_d}{T}), a_1 = k_p(1 + \frac{2T_d}{T}), a_2 = k_p \frac{T_d}{T}$.

Equation (9) is the PID control algorithm used in the intelligent infusion system, the program diagram is shown in Figure 2.

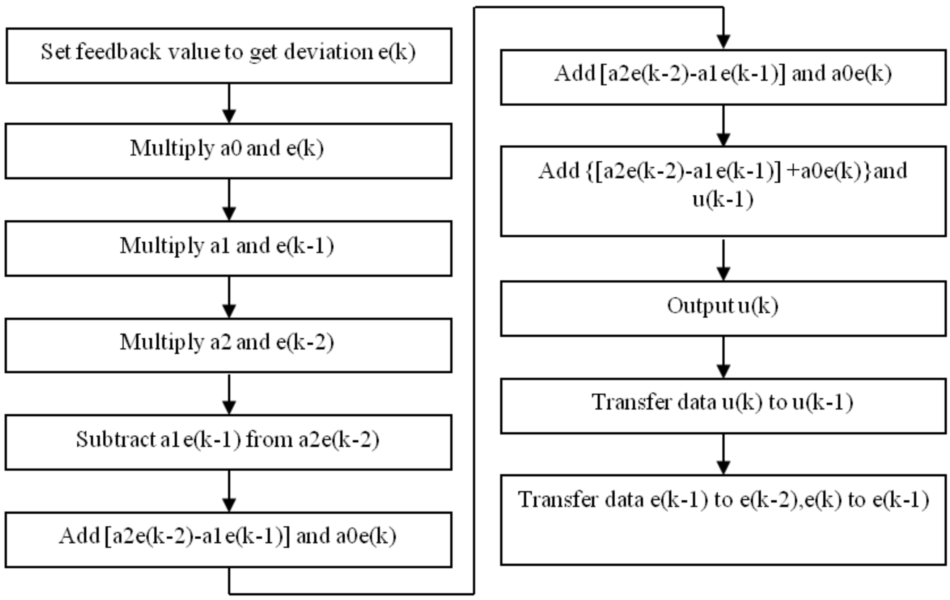

Figure 2. PID Control Algorithm Program Diagram

2.5. Empirical Analysis of the Control Performance

To study the performance of the fuzzy controller with self-adjusting factors, the mixed empirical analysis is used in this paper. On one side, under the same control object, compare this controller to the fuzzy control fixed adjusting factors, on the other side, by changing the parameters of the control objects, observe the robustness.

Selecting the typical second order link as the control object, the parameters of the control objects and performance data of the two kinds of fuzzy controller is shown in Table 1.

Table 1. Comparing of the Performance of Fixed Adjusting and Auto Adjusting Fuzzy Controller

Parameters		Fixed adjusting fuzzy controller		Auto adjusting fuzzy controller	
T1	T2	t_s	6p(%)	t_s	6p(%)
0.5	1	1.9	0	1.6	0
0.8	1.5	4.2	0	3.1	0
1	2	6.8	2.1	5.2	2.1

The response curve of the two controllers is shown in Figure 3. In Figure 3, curve 1 represents the fixed adjusting fuzzy controller, curve 2 represents the auto adjusting fuzzy controller.

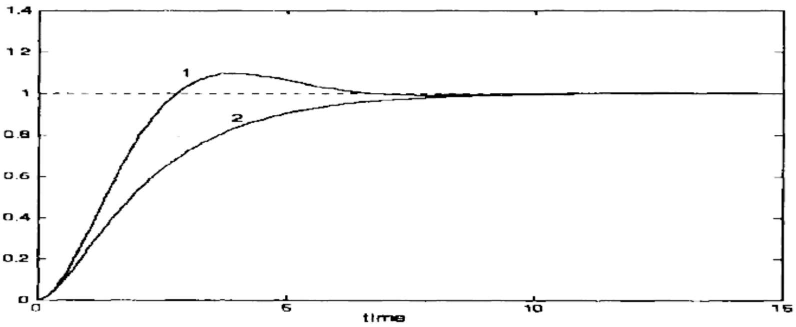

Figure 3. The Response Curve of the Two Controllers

From the performance data and the response curve, the auto adjusting fuzzy controller has low response time and overshoot, and it also has better robustness on the changing of variables than the fixed adjusting fuzzy controller.

3. System Structure and Major Function Module Design

The intelligent infusion system in this paper uses non-contact infrared technology for accurate measurement of infusion dripping speed, this technology can effectively reduce the rate of infusion infection compare to other measurement methods; ZigBee technology is also used to construct the wireless sensor network (WSN), this technology can automatically organize the network on itself. The intelligent infusion system can monitor infusion speed of multiple terminal nodes in real-time, also it can alarm the medical staff of the abnormal situation in time through the wireless network.

The hardware of the intelligent infusion system is mainly composed of drop speed detection module, speed control module, terminal module, the alarm module, ZigBee wireless module, Wi-Fi module, gateway module and routers

The design of the system’s software adopts the idea of modular and structure design. The system software includes system initialization module, main control module, monitor and alarm module, infusion speed learning and memory module, display module, network protocol module, background database and web server module.

The background database can store personal information, drugs using information, server software using a particular algorithm or mathematical model to predict the patients' infusion drip speed. Medical personnel can check the patients' information, medical information, and monitor real-time infusion process (drop speed, quantity surplus, alarm) through PC or mobile terminals.

With microprocessors, wireless transmission network, highly intelligent system software and hardware design, the intelligent infusion system realized the remote monitor and management through combining the upper machine (PC) and the lower machine.

The system structure is shown in Figure 4.

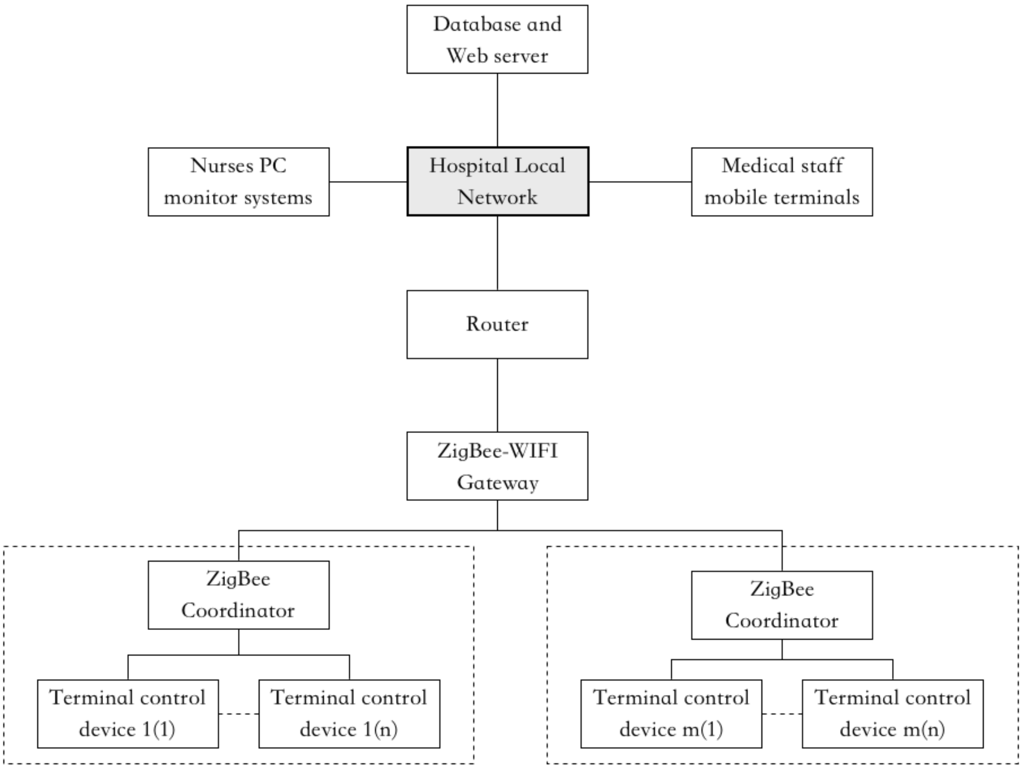

Figure 4. The Structure of the Intelligent Infusion System

3.1. Stepper Motor Drive Control

This paper selected a stepper motor of 12V rated voltage, 1.2A rated current as the driving force of the intelligent infusion system. Digital control and accurate positioning with self-lock capability are easy to realize in the stepper motor. With the stop of input electrical impulses and maintain the current of the last pulse controlled winding, the stepper motor can lock on the fixed position.

The stepper motor is controlled by a sequence pulse current from a single chip microcomputer. The rotation angle of the stepper motor is proportional related to the pulse frequency, and the direction of the rotation is related to the order of the pulses. This paper uses an AT98C51 single chip's P1.0, P1.1, P1.2, P1.3 of P1 line to connect to the winding of the stepper motor. The P1.0 connect to port A, P1.1 connect to the port B, P1.2 connect to the port C, P1.3 connect to the port D. The control scheme is four phase eight beats as shown in table 2.

In order to prevent over-current and improve driving characteristics, a current limiting resistor should add to the stepper motor. Due to a large amount of power the stepper motor needed in locking, the resistor will also consume large amounts of power. The resistor must have high load capacity, as well as the switch tube. Full voltage drive way is used in the control of the stepper motor, and the driving circuit is shown in Figure 5.

Table 2. The Control Model Table of the Stepper Motor

Step	P1 output status	Winding	Control
1	00000001	A	01H
2	00000011	AB	03H
3	00000010	B	02H
4	00000110	BC	06H
5	00000100	C	04H
6	00001100	CD	0CH
7	00001000	D	08H
8	00001001	DA	09H

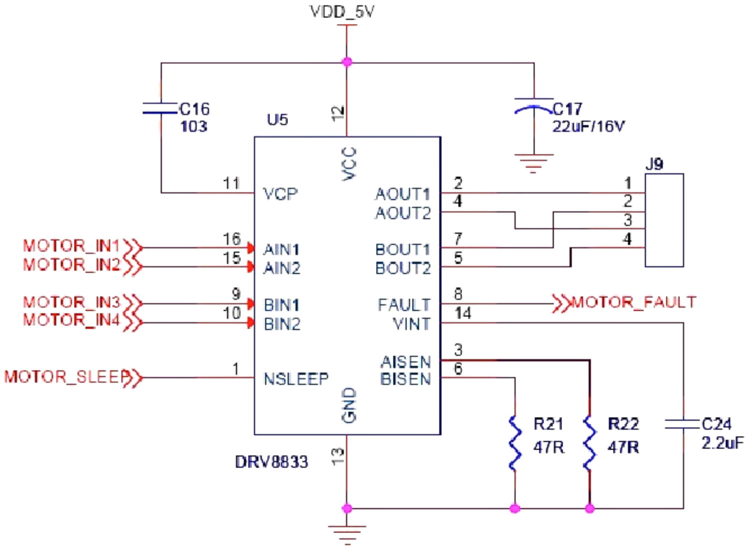

Figure 5. The Circuit Diagram of the Stepper Motor

3.2. The Software Design of the Lower Computer

The flowchart of the main program in the lower computer is shown in Figure 6.

The program of the lower computer mainly accomplishes the dripping speed detection, display and fuzzy control, liquid level detection and alarm, receive data and commands. After the initialization, the program starts to check the dripping speed, when the detection speed is deviate from the setting speed, based on the deviation e, the program can use appropriate algorithm program; when $e \geq \varepsilon$, the fuzzy control algorithm program is used, when $e < \varepsilon$, the PID control algorithm is used. In the circulation, if the serial interrupt happens, the program would go into serial interrupt receiving/sending the program, and all the other lower computers adopt the same way as interrupt receiving/sending mode.

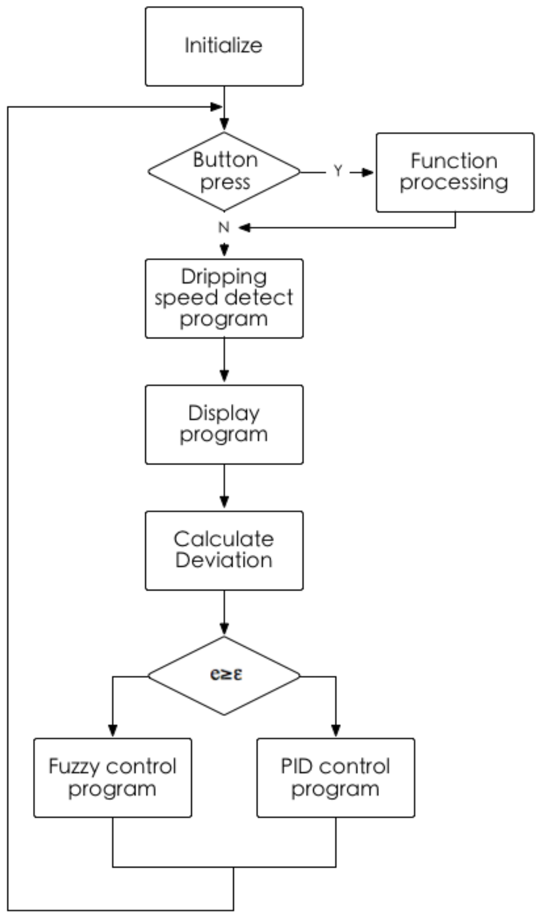

Figure 6. The Flowchart of the Main Program of the Lower Computer

4. The Implementation of the Fuzzy Controller

The control of the dripping speed uses fuzzy-PID compound control algorithm, this algorithm can increase the system's precision as well as improve the system overall performance. The infusion speed deviation e and deviation rate ec are the input variables of the fuzzy controller, the increment steps u of the stepper motor is the output variable of the fuzzy controller, the control diagram is shown in Figure 7.

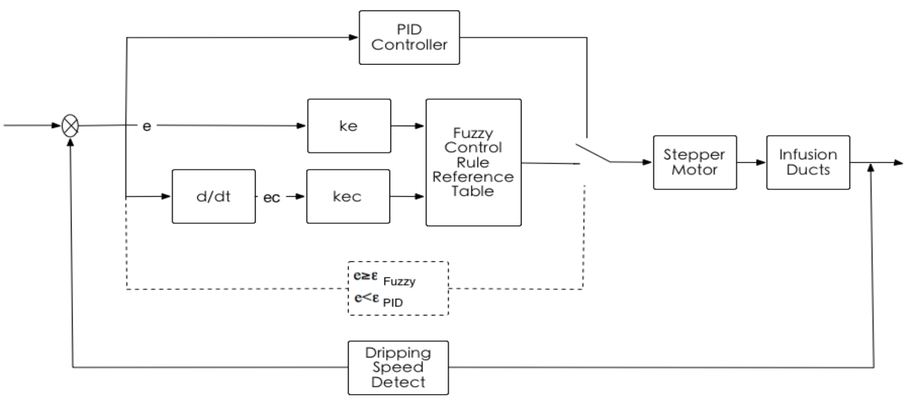

Figure 7. The Control Diagram of the Fuzzy-PID Controller

5. System Testing

After the debugging of the system software and hardware, write the lower computer software to the single chip's flash memory, connect the circuit, and test the system in practical environment. The dripping speed is set by the mobile terminal and after 30s the dripping speed is observed with stopwatch. The result is shown in the Table 3.

Table 3. The Dripping Speed Test Result

Base Dripping Speed(drops/minutes)	System Setting/Displayed Dripping Speed (drops/minutes)	Observed Interval (seconds)	Observed Dripping Speed (drops/minutes)
44	101	30	100
43	98	30	98
43	75	30	76
44	54	30	53

The test results show a very satisfied response time from the set of dripping speed to the destination dripping speed, and the results also show that the observed dripping time deviated little from the displayed dripping time.

6. Conclusion

In the clinical practice, the infusion dripping speed generally adjusted by nurses manually. The adjustment is mainly based on the nurses' experience, and the adjustment is not accurate and convenient enough for the safety of the patients. The nurses also can't response timely to the empty infusion bottle. This paper proposed an intelligent infusion system, with the using of fuzzy-PID control method on the dripping speed, the system can achieve real-time dripping speed adjustment through the mobile terminal, also any abnormal status in the infusion process, the system can alarm the medical staff through mobile and PC terminal.

To fulfill the purpose of the intelligent infusion system, a new fuzzy control method is described in this paper. This control method combines the fuzzy control and PID control with auto adjusted factors, comparing to the conventional fuzzy controller, this new fuzzy-PID controller are characteristics by it's short response time and high accuracy.

The test results show the validity of fuzzy-PID controller using in the intelligent infusion system, and the system is capable of reducing the workload of the medical staff while improving the safety of the patients.

In some circumstances, such as emergency, the infusion dripping speed must set to an extremely high value; the application of the intelligent infusion system under those extremely situations remains untested. The reliability of the intelligent infusion system still needs verification in long time usage in the further research.

Acknowledgment

This project was supported partially by, Population Health Informatization in Hebei Province Engineering Technology Research Center,Medical Informatics in Hebei Universities Application Technology Research and Development Center,Hebei province department of science and technology project(15217747D), Hebei province department of education youth fund project(QN2014182), Zhangjiakou department of science and technology project (1421012B and

1421054I) and Hebei North university field project (No.ZD201301, N0.201302, N0.201303, No.Q2014002 , No.Q2014005 , No.Q2014008).

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