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Development of Fuzzy Logic Based Temperature Controller for Dialysate Preparation System

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***Abstract*—Preparing the dialysate temperature to the desired level is a complicated task, since it has a large degree of time delay and nonlinear behaviour. In this work, embedded system for dialysate temperature controller was developed. It is based on implementation of fuzzy logic controller software on STM32 F4 development kit which consits of ARM Cortex M4F microcontroller. The dialysate temperature was controlled by varying the firing angle of the triac which is connected to the heater. The K-type thermocouple which is connected to AD595CQ was read and compared with the desire dialysate temperature. The fuzzification process was conducted prior to activate the fuzzy inference process. The power of the heater was adjusted based on the output of the inference process until the desired water temperatur was achieved. The system had been sucessfully demonstrated for controlling the dialysate temperature.**

***Keywords*—embedded system, fuzzy logic controller; hemodialysis; microcontroller; temperature controller**

Introduction

Temperature is an imporant control parameter in hemodialysis. Maintaining the dialysate temperature within the physiological range is an important for patient safety. The normal temperature range for dialysate is in between 35 ^{0}C and 41 ^{0}C. A temperature grearer than 42 ^{0}C denatures protein and results in hemolysis. A temperature less than 35 ^{0}C degrees may produce chilling and hypothermia [1]. A visual and an audible response is required for a temperature alarm and dialysate flow will be diverted from the dialyzer during a temperature alarm.

The temperature controller for the dialysate has an important role in the hemodialysis machine. For controlling the temperature, the method of heating and cooling control phase method was usually adopted. The heating input comes from the heater, while the cooling input directly comes from the inlet water. The heating system usually has time-delay and temperature dependence nonlinear behaviours. It is hard to establish an accurate dynamic model for a controller design. Generally, it needs a trial-and-error process for obtaining a good control response. When the system has external disturbance or set-point change, its transient response may deteriorate. It needs to readjust it or switch it to the manual control. This is not a convenient application for the hemodialysis machine and the dialysate temperature can not be maintained in a good level during hemodialysis treatment process.

Currently, most of the temperature controllers employed in the industrial process controls use the conventional proportional-integral-derivative (PID) controller due to its simplicity in structure and ease of implementation [4]. However, there is some disadvantages in utilizing such a conventional PID controller, since it is hard to search the model-free appropriate control gains for achieving good dynamic performance. The selected constant PID control gains can not achieve consistent control accuracy for different temperature setting points.

Recently, the fuzzy control theory is used to improve the adaptivity and robustness of a PID controller. There has a lot of fuzzy PI, fuzzy PD and fuzzy PID control schemes were proposed in literature [4]. The PID gains are nonlinear functions of tracking control performance. They can be adjusted automatically based on the output error. It can achieve better robustness, quick response and smaller overshoot than that of a traditional PID controller.The fuzzy logic controller has also been sucessfully used for controlling the temperature of furnace [5].

This paper presents the design and implementation of a fuzzy logic temperature controller on dialysate preparation system. The code was written in C and implemented on STM32 F4 development kit. It is a fuzzy logic based an embedded system for an online temperature monitor and control system. The system had been sucessfully demonstrated for monitoring and controlling dialysate temperature.

Methodology

Electronic System Design

Figure 1 shows the block diagram of dialysate preparation system. It consists 3 chamber: water inlet storage chamber, water heater chamber, and dialysate storage chamber. Purified water is introduced to the storage chamber trough a inlet valve 1 and filter 1. The water is transported through a heat exchanger before entering the heater chamber. Excess of water was removed from the chamber trough valve 2. Water temperature is meaured using a type K-thermocouple (Chromel-Alumel). The K-type thermocouple has an effective Seebeck coefficient of about 41μV per degree change in temperature. After the water temperature reachs the desired level, the heated water was transported to the final fresh dialysate storage chamber and mixed with bicarbonate and acetate solution. The dialysate liquid is then distributed through the entitre loop with a flow pump. The heating capacity given to the system is depending on the water inlet and desired water temperature, as well as the dialysate level on the final fresh dialysate storage chamber. Therefore, the system is considered to be a close-loop system, which means that if a controller sents out signals to turn on the heater to achieve a desired temperature set points, temperature feed back which is the instantaneous value of the resulted action will be substracted with the set point input to obtain the error.

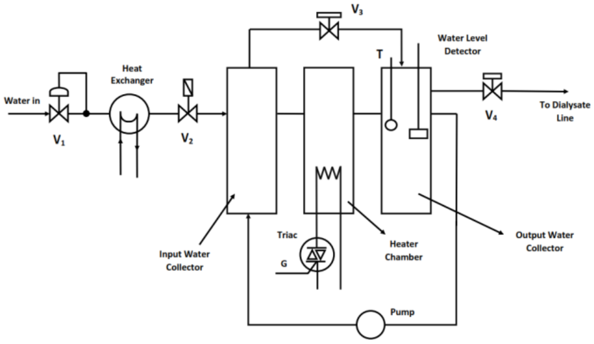

Figure 1. Schematic Diagram of Dialysate Preparation System

The electronic system has two main task : monitoring and controlling the water temperature. The amount of water introduced in the heater chamber depends on the water level on the water storage chamber. A microcontroller will be programmed with the fuzzy knowledge base rule. The temperature sensors were interfaced with the microcontroller to monitor the water temperature. A level indicator circuit was interfaced with the microcontroller which will indicate the water level inside the chamber. Fuzzy Logic Controller consist of temperature control manifested in the form of fuzzy relation between the present temperature to be controlled and the desired set-point temperature. The fundamental nature of fuzzy control algorithm is the conditional statement between fuzzy input variable (present water temperature) and fuzzy output variable (heater power).

In the fuzzy logic controller, the actual temperature is read and compared with the corresponding to set-point temperature. The error-count is used to trigger the fuzzy inference process. This develops an overall power for heater control that maintains the water temperature to the set value. Water temperature is meaured using a type K-thermocouple (Chromel-Alumel).

Circuit diagram of the fuzzy logic temperature controller is depicted in Figure 2. It consists of temperature acquisition system, microcontroller unit, zero crossing detector, and heater actuator.

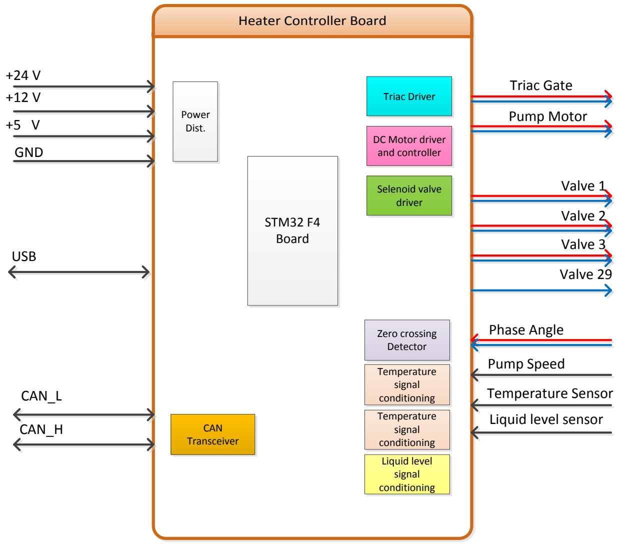

Figure 2. Schematic diagram of embedded system for temperature controller

Temperature acquisition system. Water temperature is measured using a type K-thermocouple (Chromel-Alumel) which is connected to AD595CQ. The analog output voltage is linearly proportional to temperature with a gradient of 10mV/ºC and able to operate in the range of -55ºC to +125ºC with an accuracy of ± 1 ºC (Max). The analog output of the AD595CQ was fed to analog input of the microcontroller for digitization. The digitized signals was processed to get the actual physical water temperature.

Microcontroller Unit: The system circuit diagram has been designed around the ARM Cortex M4F microcontroller. The microcontroller’s on-chip peripherals like programmable I/O port, Timer and External Rest, RC-oscillator, EEPROM, Power On Reset (POR) are being used to lower the cost and to increase the efficiency and reliability. This makes the ARM Cortex M4F microcontroller a better choice for such embedded systems.

Zero crossing detector: The zero crossing detector was employed to fire triac exactly at the zero point of the AC cycle. Zero crossing detector generates pulses for every zero crossing of the input AC signal. These pulses are fed to the interupt pin of the microcontroller through the opto-coupler. The opto-coupler is used for the isolation of the high voltage AC to the low voltage DC supply at the microcontroller side.

Heater actuator: The power of the heater was controlled using triac BT136 which can operate directly on the 220V main and a maximum load current typically 5A. Phase angle control technique is employed to control the load power. The output power is controlled by the phase delay of the triac drive. This delay is referred to the zero crossing of the line voltage detected by zero crossing detector circuit. The control output from microcontroller port pin was connected to opto-coupler MOC3031M for triggering the triac.

Embedded Software Design

Sequence diagram of the temperature control software is shown in Fig. 3. The software has two main tasks: controlling and monitoring dialysate temperature. It consists of various tasks such as schedulling (scheduller), device controller (devcontroller), normalizer, and algorithm fuzzy logic controller. The operation of an fuzzy logic controller at time t consists of three sequential steps known as fuzzification, inference and defuzzification. The fuzzification step converts the crisp values of the system inputs into fuzzy values. The inference step utilizes the fuzzy input values to activate the relevant fuzzy rules and generate the corresponding fuzzy output values. Lastly, the defuzzification step converts the fuzzy output values into crisp values [9].

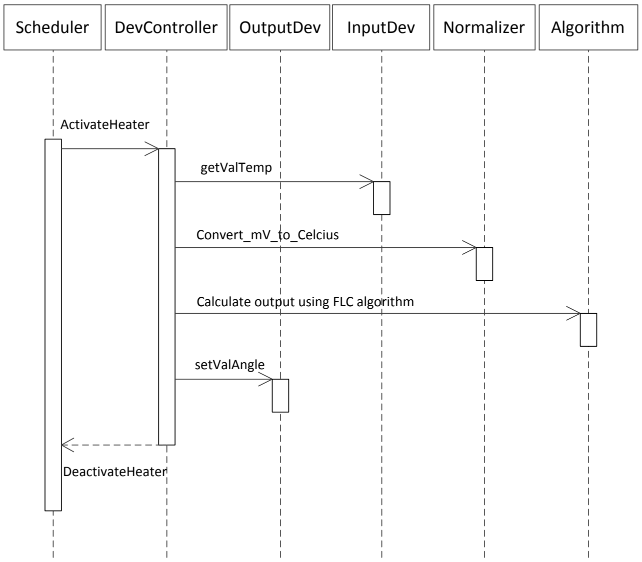

Figure 3. Sequence diagram of temperature control

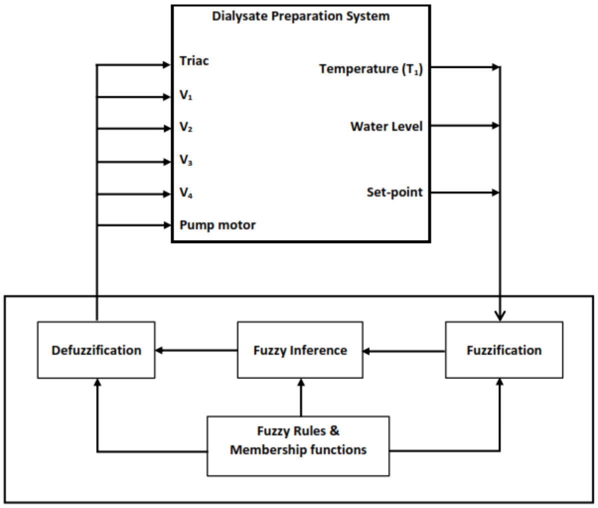

Figure 4. Fuzzy logic controller

The fuzzy logic controller was designed to have two inputs and multiple outputs as shown in Fig.4. The input variables are the water temperature and water level. The output variables are the firing angle for the triac which is related to the amount of power delivered by the heater, three selenoid valves, and one pump. The membership functions divide the entire range universe of discourse of the input and output variables into a few subranges represented by the fuzzy states. The graphical representations of the fuzzy membership function for input linguistic variables of water temperature and water level are shown in Fig. 5 and 6, respectively.

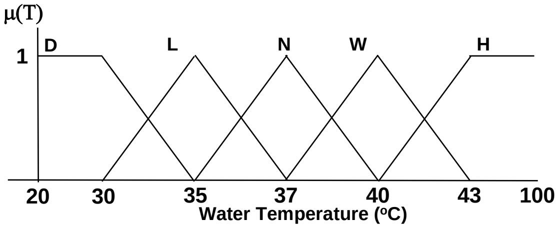

Figure 5. Membership functions for water temperature

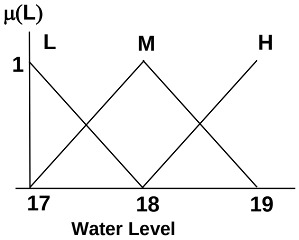

Figure 6. Membership functions for water level

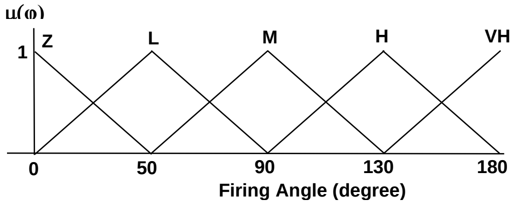

Figure 7. Membership functions for firing angles

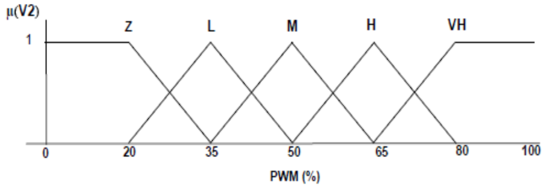

Figure 8. Membership functions for inlet valve

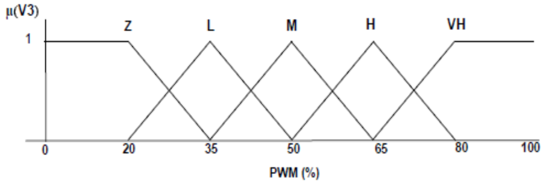

Figure 9. Membership functions for cooling water valve

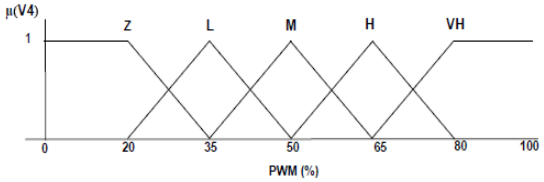

Figure 10. Membership functions for outlet valve

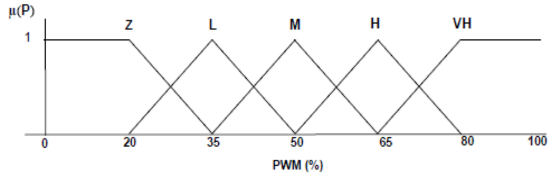

Figure 11. Membership functions for circulation pump

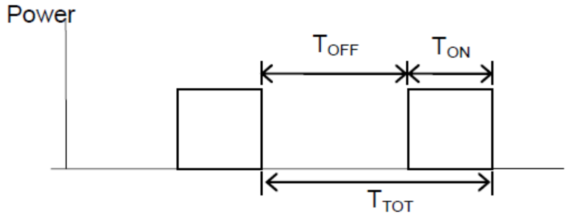

Figure 12. PWM for driving the valves and pump motor

The output linguistic variables express linguistically the applied values to firing angles of triac controlling the heater. It is necessary to assign fuzzy memberships to output variable, similar to the input variable. The fuzzy sets used for firing angle are as follows: Z = zero, L = low, M = medium, H = high, VH = very high. Fig. 7, 8, 9,10, 11 show the graphical representation of the membership functions for output linguistic variables of firing angle, inlet valve, cooling water valve, outlet valve and pump. Procentage of the PWM represents the ratio between T_{ON} and T_{TOT} multiplying with hundred percent. Reprecentation of T_{ON} and T_{TOT} can be shown in Fig. 12.

Table 1. Fuzzy linguistic of input and output system

Parameters	**Type**	**Min**	**Max**	**Denomination**
Water temperature (WT)	Input	35	40	ºC
Water level (WL)	Input	17	19	cm
Firing angle (HT)	Output	0	180	degree
Inlet water valve (V2)	Output	0	100	PWM(%)
Cooling water valve (V3)	Output	0	100	PWM(%)
Outlet water valve (V4)	Output	0	100	PWM(%)
Circulation pump (P)	Output	0	100	PWM(%)

Once the values of the input variables are fuzzified, the fuzzy controller continues with the phase of making decisions what actions should be done to bring the temperature to its set-point value. The criteria for this action are minimum time and minimum temperature oscillation [10]. The rule blocks contain the control policy of a Fuzzy Control System. The rules 'IF' part describes the situation, for which the rules are designed. The 'THEN' part describes the response of the fuzzy system in this situation. The control policy of the system is structurally formulated in terms of fuzzy rules as shown in the following lists:

R-1 : IF (WL is L) and (WT is D) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-2 : IF (WL is L) and (WT is L) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-3 : IF (WL is L) and (WT is L) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-4 : IF (WL is L) and (WT is N) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-5 : IF (WL is L) and (WT is W) then (P is H) and (HT is H) and (V2 is L) and (V3 is H) and (V4 is L)
R-6 : IF (WL is L) and (WT is H) then (P is H) and (HT is H) and (V2 is L) and (V3 is H) and (V4 is L)
R-7 : IF (WL is M) and (WT is CD) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-8 : IF (WL is M) and (WT is CL) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-9 : IF (WL is M) and (WT is L) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-10: IF (WL is M) and (WT is N) then (P is H) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-11 : IF (WL is M) and (WT is W) then (P is H) and (HT is H) and (V2 is L) and (V3 is H) and (V4 is L)
R-12 : IF (WL is M) and (WT is H) then (P is H) and (HT is H) and (V2 is L) and (V3 is H) and (V4 is L)
R-13 : IF (WL is H) and (WT is CD) then (P is L) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-14 : IF (WL is H) and (WT is CL) then (P is L) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-15 : IF (WL is H) and (WT is L) then (P is L) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-16 : IF (WL is H) and (WT is N) then (P is L) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-17 : IF (WL is H) and (WT is W) then (P is L) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)
R-18 : IF (WL is H) and (WT is H) then (P is L) and (HT is H) and (V2 is L) and (V3 is L) and (V4 is L)

The output of the defuzzification must be in the numerical form. The following equation is used to obtain the crisp output [11],

$$D = \frac{\sum_{i=1}^{N} \mu[i] W[i]}{\sum_{i=1}^{N} W[i]} \tag{1}$$

where µ[i] and W[i] is the peak values for i^{th} output membership function and the weight associated to the i^{th} rule, respectively.

To measure the performance of the system, the following quantitative measures are used, namely IAE (integral absolute error), ISE (integral square error) and ITAE (integral time absolute error). Mathematical expresions for such quantititive measures are given as follows,

$$IAE = \int_0^\infty |e(t)|\, dt \tag{2}$$

$$ISE = \int_0^\infty e^2(t)\, dt \tag{3}$$

$$ITAE = \int_0^\infty |e(t)|\, t\, dt \tag{4}$$

Results

The temperatures in the case study are as follows: set temperature = 35°C; and current temperature = 30°C. Using the data acquisition system that had beed developed, real time of water temperature data are collected. Fig. 13 shows the graph of temperature versus time. It can be observed that after 50 second, the set point temperature is achieved. The steady condition is achieved with the deviation around ± 0.5 °C of set point. It means that the real time result is acceptable.

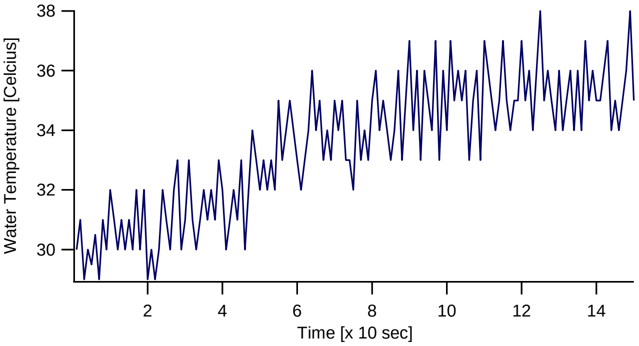

Figure 13. Temperature as a function of time

From the experimental data, the values of IAE (integral absolute error), ISE (integral square error) and ITAE (integral time absolute error) are 3.46, 0.16, and 167.8, respectively.

Conclusion

The fuzzy temperature controller is designed and implemented in ARM Cortex M4F microcontroller with minimum cost. Few rules and membership functions for both inputs and outputs had been developed using C and implemented into the microcontroller to solve a temperature control problem with unknown dynamics or variable time delays of dialysate preparation system. The hydraulic and electronic systems had been developed with minimal cost for testing the fuzzy logic controller algorithm. The control result can be improved by finer tuning for the membership functions and resizing the fuzzy rules.

a.

Acknowledgment

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