Application of fuzzy logic in hemodialysis equipment

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Abstract — **In hemodialysis machines peristaltic pumps are responsible for the transfer of fluids. These pumps can only deliver the solutions with significant error, due to the deviation of the pump head and due to production errors. Previous work focused on system identification and fluid flow control by a PID controller. In this paper the goal is to replace the PID controller with an adaptive fuzzy controller. Furthermore, the use of integral component for error signal rejection is examined as input to the fuzzy logic system. The mentioned controllers are compared through appropriate aspects and the paper ends with discussion of the behavior of the adaptive fuzzy controller on the real system.**

I. Introduction

In hemodialysis machines, peristaltic pumps maintain the fluid flows (such as blood, dialysate or replacement flow) [1–3]. The reason for this is that peristaltic pumps exert small shearing force on the transported fluid (less chance of hemolysis in case of blood pump [4]) and the used substitution keeps its sterility as the fluid comes in contact only with tubing instead of the pump (also it is possible to use disposable kits for it) [1].

Peristaltic pumps contain a manifold, a pump head and an elastic tube. The pump head typically has a rotor part and two or more rollers. During transfer the rotor revolves; hence, the roller presses the elastic tube to the manifold that prohibits the black-flow of the fluid. As the pump head rolls forward a pressure wave is generated in the pump segment pushing forward the fluid in the tubing [5]. Before the first roller leaves the manifold and releases the tube segment, a second roller presses the elastic segment to the manifold. This way a constant flow can be kept and black-flow is impossible.

The main characteristic of peristaltic pumps is that their transfer volume mainly depends on their loaded tube segment. As a result, due to production errors their transfer volume can differ by ±10% in comparison to what is expected [6]. This deviance can mean significant error especially at higher flow rates. In terms of medical fluids (sometimes drugs), controlling the fluid balance of the patient is important to be done as accurate as possible [4], [7]. Therefore, a direct linkage appears to control engineering on the pump rotation speed.

Previous work focused on system identification and control possibilities using classical control approach. A simple Mamdani-type fuzzy logic and a PID controller was compared, and based on the quality parameters obtained the PID controller was chosen to be implemented in practice [8].

In this paper the same identified system is used and modern soft-computing control possibilities are examined with the help of fuzzy logics. The formerly defined properties of the previous controllers are compared to the properties of two new solutions using fuzzy logic. The formerly designed Mamdani-type fuzzy controller used the error signal of the system as input and had significant residual error [8]. Now, the idea is to design two controllers: one that uses the integral of error signal as input and a second implementing an adaptive controller. The goals are to remove the residual error of the first fuzzy controller and to implement an adaptive controller without any supplementary algorithm. Finally, the adaptive fuzzy logic solution has been implemented in practice and the differences between the simulated and real controller are discussed as well.

II. Methods

A. Short review of former results from [8]

In our previous work [8], the system was identified with different methods: Box-Jenkins, ARX and ARMAX methods. Subspace identification proved to be the most accurate, resulting in the following transfer function:

$$H(s) = K_{pump} / s \qquad (1)$$

For simulations two plants have been used. The first plant simulates the real system; for input, it receives the desired fluid flow, which is connected to the identified system. As a result, the transferred fluid volume is produced. The other plant includes error sources. The input can be modified through a gain, which simulates the slope error of the system. The slope error refers to the deviation caused by production of the tube segment; hence, this needs to be corrected first. Moreover, a specific amount can be added to the output, which results in an offset error. This can simulate improper transfer volume, error in the weight measurement, or if not a constant value is used it could mean a random kind of disturbance. (More values can be added at the same time, in this way one or more of the mentioned error sources can be simulated.) The output of the second plant can be subtracted from the output of the first plant, which results in the error signal. This error signal is connected to a subsystem, which represents one of the controllers. The output of the controller is connected to glue logic in order to simulate the real calculations in the machine, which is necessary for the intervention (Fig. 1).

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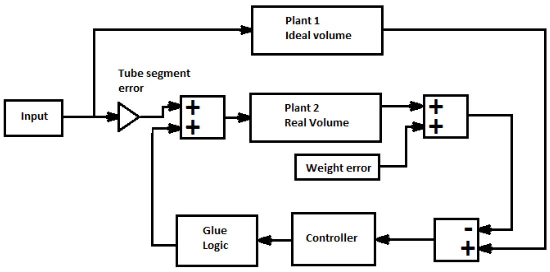

Figure 1. Schematic figure of examined model

The controllers' quality parameters were set in [8]:

- settling time;
- overshoot;
- accuracy;
- robustness.

From these properties the overshoot seems to be less important, as the controllers provided very similar results in these cases. In the case of settling time, the lower flows are important, because the whole system works slower and in this way more time can be lost with slower controllers. The most important property proved to be the accuracy. This can be examined by measuring the residual error. In terms of drugs, medical fluids and patient fluid balance one of the most important tasks is to eliminate the residual error; hence more advanced control methods are required like soft-computing techniques.

The examined flows in [8] were set in low, medium and high flow possibilities (300, 1500 and 3000 ml/h). Now a smoother resolution is used: 100, 300, 500, 1000 and 1500 ml/h. These reflects the mostly used intervals [9–11].

B. Controller design

In [8] the PID controller was designed for 60° phase margin. For the fuzzy system, the two ends of the control range were covered with z-shaped membership functions. Between these points, triangular-shaped membership functions were used. The 19 membership functions were weighted from 1% to 50% with the following patterns: 1%-2%-5%-10%-20%-etc. [12]. Both the PID and fuzzy controllers received the difference between the ideal transferred volume and the weighted one with errors as input.

During the application some difficulties arose regarding these controllers. On one hand, the fuzzy controller was unable to remove the residual error, which is unacceptable in terms of drugs and patient fluid balance. On the other hand, the task of the controller is to find the real operating point of the system (difference caused by the production deviation of the elastic tube segment) and to control the system in this new operating point. To fulfill this criterion, the adaptive property was introduced for the controller. This requires a supplementary algorithm in the case of the PID controller, but the fuzzy one can be easily expanded to be adaptive.

In order to solve these problems, two Mamdani-type [13] fuzzy controllers were designed. One is completed with the integral of the error signal as input (hereinafter "*integro-fuzzy*") and another fuzzy controller, which is adaptive (hereinafter "*adaptive fuzzy*").

Fuzzy logic is a system, which works on numerical data and converts it into a symbolic form through a data base (fuzzyfication) (Fig. 2).

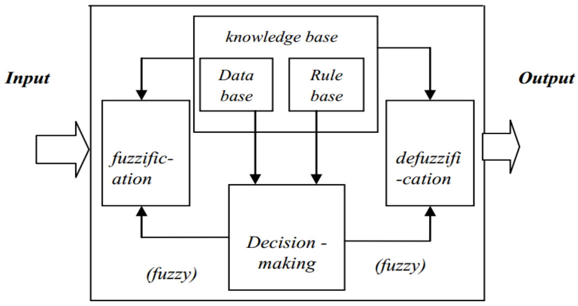

Figure 2. Schematic figure of a general fuzzy controller [15]

The logic of decision-making (rule base) is implemented; thus, it is possible to provide a symbolic answer, which must be converted into an item of numerical data (defuzzyfication) (Fig. 2) [14], [15].

As previously mentioned, one of the tasks is to eliminate the residual error. The original fuzzy controller used only the error of the transfer volume. It is a common practice to use the derivative of the error signal in order to determine the control signal. In our case this is not recommended, as the resolution of measuring the weight is 1 gram (g), thus the quantization error is high, which would be emphasized with the use of derivation. To bypass this problem, the integrated value is connected to the inputs of the fuzzy logic solution next to the original error signal. It is expected that a small error signal induces a higher control signal, and in this way the integral error will increase and trigger the mentioned growth in the control signal.

The error signal is covered in the fuzzyfication process by with 7 membership functions. Five of these are triangle shaped and the two extremities are trapezoid membership functions, which both outreach the threshold ±50 g. Over ±50 g error the output is saturated at this exact value. This threshold is defined as an empirical limit, above that the error can be treated uniformly as "extreme high/low". The membership function "MinErr" refers to the minimum error (located in the middle of the error range) and is the tightest of all the other membership functions. The other four triangle and two trapezoid membership functions cover the full range near equidistantly, but to the extremes the covered ranges increase slightly.

The integral of the error signal is covered with 5 membership functions. Three of them are triangle shaped, the others are trapezoid membership functions. The trapezoid membership functions outreach the thresholds ±200 g and the integral of error signal is also saturated at ±200 g. The membership functions cover the full range equidistantly.

When using the PID controller, if the control signal reaches its maximum and goes to saturation a special phenomenon can be experienced. Significant error can accumulate during this time, which can cause high overshoot and longer transient time, when control signal reaches its working range again. This phenomenon is known as windup and the logic preventing it is called the anti-windup system [16], [17].

It is practical to use such a similar system in the fuzzy controller as well. This will prevent the unnecessary increase of the integral of error if the control signal is in saturation. In order to do this, the output and the saturated value of the output are compared. A switch is operated with the result of this comparison. If the output is not saturated, then the error signal is pronounced on the output of the switch, otherwise a zero value is integrated over time.

In the defuzzyfication process, the output is covered with 9 membership functions. Seven of them are triangle shaped membership functions, and as mentioned, the extremities are trapezoid ones. The covered range means here ±10% control; the trapezoid membership functions outreach the thresholds. The control signal is saturated at ±10% as well. In the middle of the range three tight trapezoid functions can be found. The central one means minimal control. These three functions are responsible for the fine control tuning. The other triangular membership functions cover significantly larger intervals and they cover equally the remaining control range.

The selected inference method for this controller is the so-called max-min method, while for the defuzzyfication method the classical center-of-gravity (COG) is used.

35 rules are defined for this controller. The goal was to keep the error signal dominant: if the integral of error can stimulate the effect of the error signal their presages agree, otherwise obstruct (Fig. 3.).

Rule examples:

If ErrorSignal is BigNegative and ErrorIntegral is Negative, then ControlSignal is BigPositive.

If ErrorSignal is BigNegative and ErrorIntegral is Positive, then ControlSignal is MiddlePositive.

If ErrorSignal is SmallNegative and ErrorIntegral is Minimal, then ControlSignal is MiddlePositive.

If ErrorSignal is Minimal and ErrorIntegral is Negative, then ControlSignal is SmallPositive.

If ErrorSignal is Minimal and ErrorIntegral is Minimal, then ControlSignal is Minimal.

When designing the adaptive fuzzy controller it was attempted to create a control signal with the use of the integral of error and iterative learning control [18–20]. Some measurements (not described in detail here) showed that the transferred volume can be controlled almost as effectively through the integral of error as with both the error signal and integral of error. Therefore, in order to preserve simplicity, only the integral of error is introduced in the fuzzy logic.

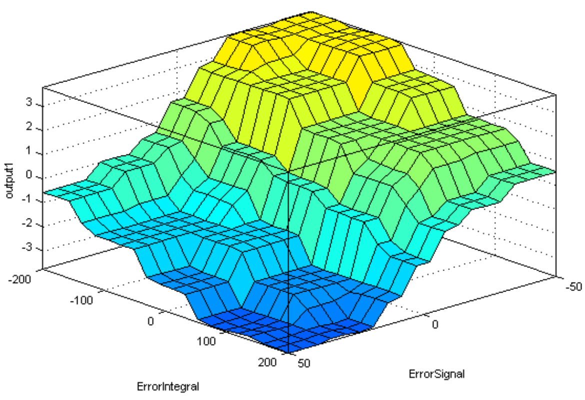

Figure 3. Surface of the integrofuzzy logic

The anti-windup method is also used on the integral input due to the reasons mentioned above. The output of the fuzzy logic is added to the feedback line; thus, an iterative learning control circuit is implemented. The basic concept behind is that fuzzy control is able to find the flow error in rough steps, while by fine steps is able to hold the flow close to the new operation point. The block diagram of the adaptive fuzzy controller can be seen in Fig. 4.

The only input (integral of error) was covered with 9 membership functions. Two of them are trapezoid membership functions on the two extremes. The acceptable error range is ±200 g*s (to stay in the range the error integral is saturated). The other five membership functions are triangle-shaped membership functions as discussed above. The width of the membership functions has increased to the extremes, and the small errors are covered with tighter membership functions than the big errors.

The output is covered very similarly; here, the maximum output signal is equivalent to 1%. The membership functions of the input of the adaptive fuzzy logic can be seen in Fig. 5.

When defining the rule base, a quasi linear compliance is expected. The appropriate size and presage output belongs to the same size and presage error if the nomenclatures of membership functions are taken into consideration. This way it is possible to create an appropriate logic with 9 rules.

Rule examples:

If ErrorIntegral is BigNegative, then OutputSignal is BigDecrementing.

If ErrorIntegral is SmallPositive, then OutputSignal is SmallIncreasing.

If ErrorIntegral is Minimal, then OutputSignal is Minimal.

III. Results

The results are evaluated through the same metric used in [8]. However, the measured flows are changed in order to better reflect the values applied in the real system. The PID controller is used as reference (comparison) for two reasons. At first it had better behavior. On the other hand, the PID controller has proved in the real system as well.

Settling time, overshot and accuracy have been examined [8]. The details of the measurements are presented in Table I-III.

The measured flows are 100, 300, 500, 1000 and 1500 ml/h.

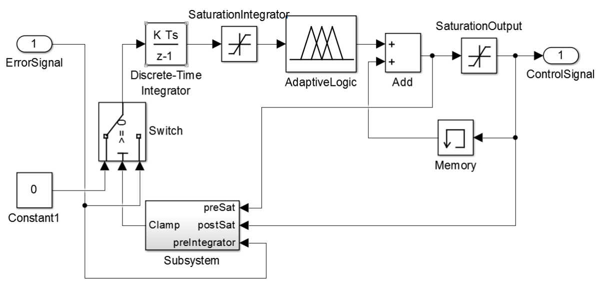

Figure 4. The developed adaptive fuzzy control scheme

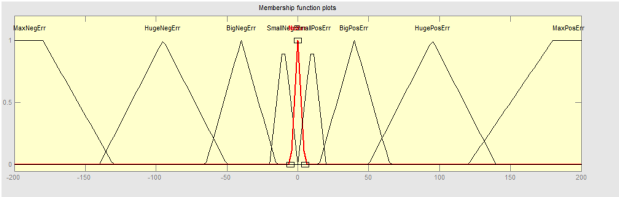

Figure 5. Membership functions of adaptive fuzzy logic input

Settling time [s]	100 ml/h	300 ml/h	500 ml/h	1000 ml/h	1500 ml/h
PID	265	267	242	239	239
Fuzzy	656	658	659	660	660
Integro-Fuzzy	1309	1247	1240	1306	1275
Adaptive Fuzzy	396	264	238	225	221

TABLE I. RESULTS ON SETTLING TIME

Overshoot [g]	100ml/h	300 ml/h	500 ml/h	1000 ml/h	1500 ml/h
PID	9	9	9	10	11
Fuzzy	1	0	0	-7	-10
IntegroFuzzy	0	-2	-2	-10	-10
AdaptiveFuzzy	2	2	2	2	2

TABLE II. RESULTS ON OVERSHOOT

When examining the settling time, the system was burdened with 5 ml volume error if a perfect tube segment is assumed (0% slope error). The 5 ml amount is a typical error in practice and the time needed to compensate was measured. The error was compensated if the error of the system is between ±1 g and the output signal of the controller is in the ±1% environment of the steady-state output [8]. (The ±1% accuracy in steady-state was the result of other system requirements.) The results are shown in Table I.

The integro-fuzzy logic has a settling time compared both to the PID controller and the original fuzzy controller. Hence, it can be said that this controller is not suitable for control, further tuning is necessary to achieve an acceptable result. On the other hand, the adaptive fuzzy controller has almost the same settling time as the PID controller. Over 300 ml/h is slightly faster, but at 100 ml/h it is slower. The results are acceptable, but faster settling would be recommended under 100 ml/h.

In order to examine the overshoot of the system, a worst case event was set: the pump segment was able to transfer 10% less fluid and at the beginning the system transferred 20 ml more than expected (-10% slope error, 20 ml offset error) [8]. The measured overshoots can be seen in Table II.

One advantage of the fuzzy controllers could be the small overshoot. The original fuzzy logic and the integro-fuzzy controller have minimal overshoot under 1000 ml/h and only over it has results similar to the PID controller. The adaptive fuzzy controller has minimal overshoot independently of the flow value.

The accuracy of the controllers was measured with the previous conditions, but the measured quantity was checked on a 200 seconds wide window (after reaching the steady-state) [8]. Results are summarized in Table III.

Accuracy [g*s]	100 ml/h	300 ml/h	500 ml/h	1000 ml/h	1500 ml/h
PID	0	0	1	0	1
Fuzzy	494	-42	-718	-5721	-8504
Integro-Fuzzy	-662	-1823	-2322	-8214	-8573
Adaptive Fuzzy	135	48	16	-51	-84

TABLE III. RESULTS ON ACCURACY

It can be concluded that the PID controller has no residual error and in steady state the volume error slightly differs from 0. On the other hand the fuzzy controllers have residual error. The size of the residual error depends on the flow and in the case of the original controller and the integro-fuzzy controller it is significant at almost any flow. The adaptive fuzzy controller has significantly smaller error in the steady state. If it is considered that these results were measured during 200 s, then it can be asserted that the error of adaptive controller is minimized. Furthermore, some trend can be seen in the case of adaptive logic, as the integral of error was decreasing with the increase of the flow. With simulations on the extremes (50 and 3000 ml/h) it was proved, that the error is sufficiently low even in this rang.

The quantitative measurement for robustness did not happen, but the system stability was checked using errors out of the tolerance range [8]. The swinging of the fluid bag was simulated with an added sinus signal on the output of the plant. The amplitude of the sine wave was chosen 10 ml, it's frequency at 0.25 Hz. A considerably bad tube segment was simulated with a 30% slope error and with 100 ml offset error. The controllers' performance was acceptable in every case as they did not reach instability.

IV. MEASUREMENTS ON THE REAL SYSTEM

The integro-fuzzy controller showed significantly worst results, than the PID controller or the adaptive fuzzy logic. However, it has been shown that it is possible to control the system with the help of the integral of error.

The adaptive controller is almost as fast as the PID controller, and at higher flows it is even faster. It has minimal overshoot and the residual error is acceptable. Consequently, it can be said, that the adaptive fuzzy logic could substitute successfully the PID controller. Furthermore, its adaptivity represents a huge benefit for embedded systems.

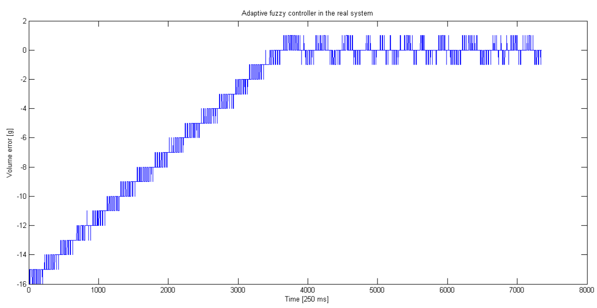

Figure 6. Behavior of the real system

The designed controller was implemented in the real system as well. The result of the measurement (at 500 ml/h fluid flow) can be seen in Fig. 6. It can be seen that the real system is significantly slower, but based on [8] this was expected. The controller was able to compensate the 20 g error introduced, while the slope error was about 10%. Moreover, in steady-state the system had almost in any cases error, but it never left the ±1 g range.

V. CONCLUSION

In this paper the control possibilities of peristaltic pumps were examined in hemodialysis systems. A previously designed and implemented PID controller was used as a reference to examine further controllers. Two fuzzy logic solutions were designed. One of the logic solutions demonstrated that it is possible to control the system with the help of the integral of error, as the derivative of error cannot be used due to the high error. The second logic demonstrated, that it is possible to design an adaptive fuzzy controller, which use the integral of error as input to control peristaltic pumps. The adaptive fuzzy logic had similar properties as the PID controller. However, in lower flows (under 100 ml/h) it is slower, but at higher flows it is slightly faster; furthermore, it has minimal overshoot. The supplementary logic, which is necessary for the PID controller to make it adaptive, can also be spared with the use of this solution.

Further research will focus on other type of fuzzy controllers as well. Moreover, we try to utilize the acquired experience in education. The research helps the development of a curriculum on the subject of identification, classical and fuzzy control design. The prepared papers can mean the basis of a new electronic lecture note [21].

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