

Identification and control of peristaltic pumps in hemodialysis machines

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Abstract—In hemodialysis machines peristaltic pumps are responsible for the transfer of fluids. The main characteristic of these pumps is that they can transport the solutions with significant error. That depends on the tube segment deviation caused through the production. Due to the fact that the medical fluid represents sometimes drugs and in the same time it is required to control the fluid balance of the patient, it is important to transfer these fluids as accurate as possible. The goal of the paper is to design a controller that satisfies the mentioned requirements. First, the system identification is realized by classical moving average method (ARX), followed by the design of two controllers: a classical PID one and a fuzzy controller. After comparing their simulation results, the most preferable one was implemented in practice. Real simulation results of the implemented controller end the paper.

I. INTRODUCTION

In hemodialysis machines fluid flows (such as blood, dialysate or ultrafiltration flow) are maintained by peristaltic pumps [1], [2], [3]. They revolve a rotor, which contains two or more rollers. These rollers press the flexible tube to the manifold where the pump is placed; hence, it creates pressure inside the tube. When one of the rollers leaves the manifold, the pressure will press the fluid further in the tube system [4]. Consequently, the blood of the patient doesn't get in contact with the pump (only with the tubing), while the peristaltic pump lowers the chance of hemolysis [5].

The main characteristic of peristaltic pumps is that their transfer volume depends mainly on their loaded tube segment. This way, due to the deviation caused through the production, their transfer volume can differ by $\pm 10\%$ than expected [6]. This deviance can cause significant error especially at higher flow rates. Due to the fact, that medical fluid represents sometimes drugs, and in the same time it is required to control the fluid balance of the patient, it is important to transfer these fluids as accurate as possible [5], [7]. Hence, this is an ideal application field for control engineering solving the problem by an adequately designed controller.

Automatic control possibilities of blood pumps are investigated by the literature [8], using classical controllers by high level code generation [9], but most of the solutions can be found as a patent as well [10, 11]. Some applications are focused on the control of ultrafiltration [12], [13], but apart from some initial projects there cannot be found relevant publications to control the fluid transfer in general.

The aim of the current paper is to propose an automatic control solution of peristaltic pumps in hemodialysis

machines. First, the system is identified using classical ARX, ARMAX, Box-Jenkins and state-space parameter identification methods. Then, two controllers, a classical PID and a fuzzy logic controller are designed on the identified system and they are compared by simulations through their main properties. Finally, the most preferable one is implemented in practice and its performance is evaluated through the formerly specified properties.

II. SYSTEM IDENTIFICATION

In order to analyze the peristaltic pump it is needed to separate it from the other part of the system. The analyzed (separated) system contains the following components: a hanged bag placed above the level of the peristaltic pump containing the solution ready to be transported, the peristaltic pump and a vessel that collects the transported fluids. By measuring the weight of the vessel, it can be determined how much fluid was transported (Fig. 1.)

A. Methodology

The main goal of system identification is to determine the system's characteristics by test signals, analyzing the response of the system to the signal in case [14]. Choosing a corresponding test signal the most important points are as follows:

- the amplitude of the test signals should be in magnitude as close as possible to the real system;
- the frequency range of the test signal has to cover the real system's frequency range.

The accuracy of the identification depends greatly on the system's noise. Regarding the peristaltic system case, the following noise components should be taken into account:

- the insecurity of the transported fluid volume;
- the quantified error of the weighing scales;
- the insecurity of the rotation on the pump head.

The first and the last noise component can be ignored, as their influence on the measurement is minimal, and they can be hardly influenced. However, the quantified error of the weighing scales can be influenced. An uncertainty on the comparison threshold can be observed during weight measurement that is reflected by a tremble. This lasts until the comparison domain is left quickly (this is the reason, why the trembling is much shorter at high fluid flows).

The first signal contains two step functions that follow each other. In case of the first one, the pump was rotated with the maximum allowed rotation, and reaching the steady-state the pump was turned off.

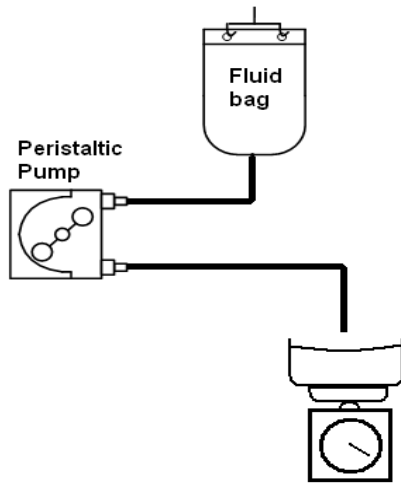


Figure 1. Schematic of the separated peristaltic pump subsystem.

After a relaxation phase the system got another constant stimulation, this time the half of the previous rotation. The steady-state and the time left for the system was specified experimentally using two rectangular signals different in amplitude and time (Fig. 2).

The other test signal was considered a periodically increasing stimulation. This signal increases every 15 minutes and it reaches the maximum allowed rotation in 20 steps. (The use of this signal will be explained later).

The identified transfer function connects the input parameter of the system (the fluid flow) with its output parameter (transferred fluid volume). For identification the ARX, ARMAX, Box-Jenkins and state-space methods were used.

The a-priori information and the system most common properties were used to specify the transfer function of the state-space model. The input signal is the fluid flow, which defines the transferred fluid volume during unit time. This is why the pump behaves as a proportional component between the fluid flow and the transferred volume. The system contains a reservoir (the vessel) as well, where the transfer fluid is measured and collected. Hence, this component works as an integrator component, because it collects the transferred fluid over time. The system has no dead-time. Consequently, the plant can be described with the following transfer function [16]:

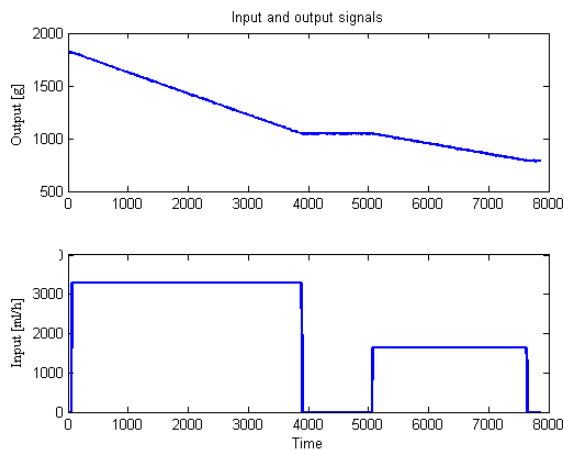


Figure 2. The test signal used for identification and the system-answer.

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

where the task is to identify the K_{pump} amplification.

The ARX model uses the following equation [15]:

$$y(t) + a_1 y(t-1) + \dots + a_{n_a} y(t-n_a) = b_1 y(t-n_k) + \dots + b_{n_b} u(t-n_b-n_k+1) + e(t) \quad (2)$$

or in a more compact form:

$$A(q)y(t) = B(q)u(t-n_k) + e(t) \quad (3)$$

where $A(q)$ and $B(q)$ are polynomials, $u(t)$ is the input of the system, $y(t)$ is the output of the system and $e(t)$ is the noise component. The main question of parameter identification is to determine the order of the $A(q)$ and $B(q)$ polynomials (n_a , n_b) and the dead-time (n_k). If one of them is underestimated the model will not be accurate enough, while overestimation will over-parameterize the system leading singularity [14].

Due to the simplicity of the system n_a and n_b was chosen 2 [14, 17], while due to lack of dead-time n_k was set 0.

B. Results

After parameter identification question arises on accuracy and computational intensity. The best solution was obtained by the state-space model, followed by the ARX, ARMAX models and at the end by Box-Jenkins model.

The accuracy of the models was checked by calculating the root mean square error [19].

$$RMSE = \sqrt{\sum_{i=1}^n (y - \hat{y})^2 / n} \quad (3)$$

where y is the model's output value at a given time, $\hat{y}$ is the measured value at the same time and n is the number of the samples (length of the measurement).

Results of the error calculation can be found in Table 1. The first line of it shows the root mean square error in the output signal's original dimension (gram). The second line reflects the root mean square error in percentage, where the error is shown as percentage of the full scale value.

It can be determined from the second line that the accuracy of every identified model is over 95%. However, the most accurate models proved to be the ARMAX and the state-space ones.

TABLE I
ERRORS OF THE DIFFERENT MODELS USING ROOT MEAN SQUARE ERROR

	State-space model	ARX	ARMAX	BJ
RMSE[g]	1,32	14,46	2,43	7,48
RMSE[FS%]	0,13	1,41	0,24	0,73

Consequently, the state-space model was chosen to support the controller design. It was not only the most simple from the mentioned models, but this was the most accurate from the examined group as well.

In order to verify the obtained model another measurement was performed. The RMSE error in percentage of the full scale value was 0.18%, which means that the model simulates the real system acceptably.

III. CONTROLLING THE PERISTALTIC PUMP

The goal of the paper was to design two controllers and choosing the best one, to realize it in reality.

The first controller was realized on the classical PID methodology (the controller needs an integrator to eliminate the residual steady-state error and due to the highest control speed a differential term), while the other one is designed on soft computing methodology using fuzzy logic. This latter one has been already proved on similar systems [20,] [21].

Fig. 3 represents the block scheme of the realized system. The identified model corresponds to a discrete transfer function. The ideal system (Plant1, the system without noise) is compared with the real one (Plant2, the system with noise components). The stimulation is amplified with a constant in order to simulate the tube segment error. Hence different errors of the load cell (the weighing scale) can be simulated like swinging, or incorrect transferred volume (Weight error). The error between the ideal and real plant represents the input of the controller. The output signal of the controller influences the glue logic.

The controlled flow range is really wide (0-3000 ml/h) and (with the highest accessible speed) the maximum error can be 3.3% in steady-state. (This last criterion comes from system requirements.)

Due to the slow characteristics of the system 60 degree phase margin was left for the PID controller [18]. For the fuzzy system the two end of the control range was covered with z-shaped membership functions [22]. Between these

points triangular-shaped membership functions were selected [23].

The quality parameters used to check the characteristics of the system were:

- settling time;
- overshoot;
- accuracy.

To measure these properties three scenarios were taken into account with different fluid flows: one with low flow rate (300 ml/h), one with medium flow rate (1500 ml/h) and one with highest flow rate (3000 ml/h).

When examining the settling time the system was burdened with 5 ml volume error, a typical error in practice. The tolerance of the system was set up at ± 1 gram, while the tolerance of the output signal for the controller was $\pm 1\%$ of the steady-state. (The $\pm 1\%$ accuracy in steady-state was the result of given standards.)

Fig. 4 summarizes the system error at medium flow rate, while the results of the measurements are summarized in Table II.

At high fluid flow rate the fuzzy controller proved to be significantly faster then the PID controller; however, lowering the flows melts the difference. At the lowest flow rate the PID controller gets faster and in this case the whole process needs significantly more time. Regarding controller speed, the PID controller proved to be the better.

From the point of the overshoot 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 (i.e. -10% slope error, 20 ml offset error).

TABLE II
SETTLING TIME EXAMINATION

Settling time [s]	@300 ml/h	@1500 ml/h	@ 3000 ml/h
PID	604	242.25	259.5
Fuzzy	659	132	65.5

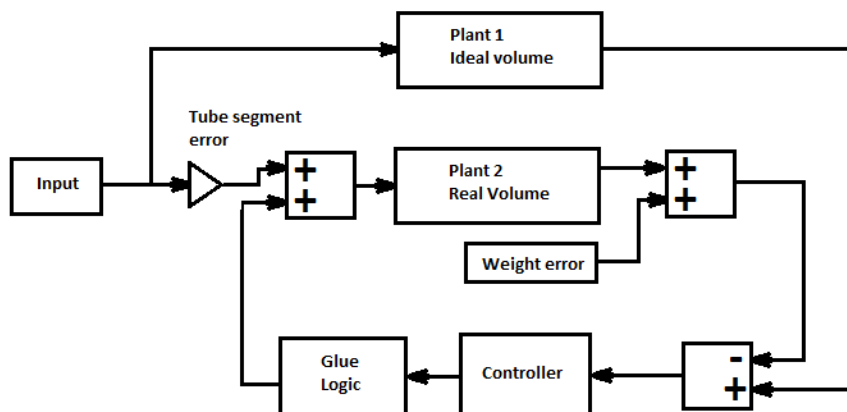


Figure 3. Block scheme of the simulated system

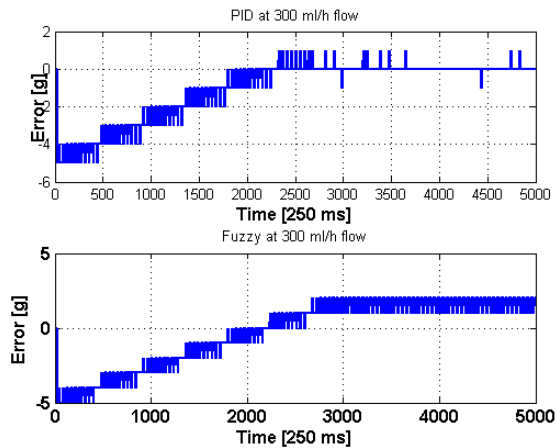


Figure 4. System error at 300ml/h flow in settling time examination

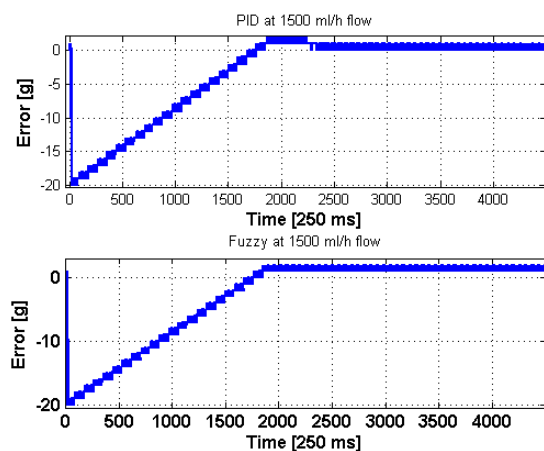


Figure 5. System error at 1500ml/h in overshoot examination

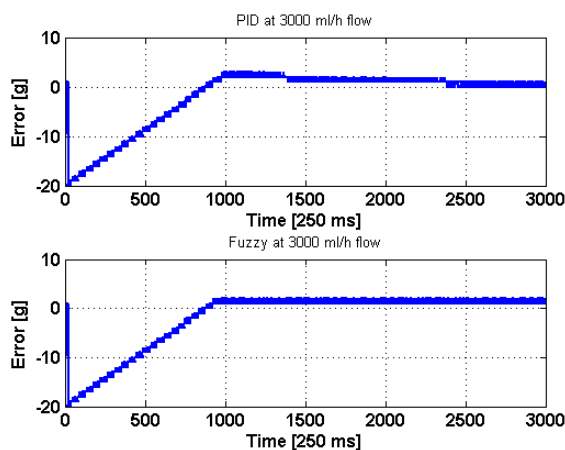


Figure 6. System error at 3000ml/h in accuracy examination

TABLE III
OVERSHOOT EXAMINATION

Overshoot [g]	@300 ml/h	@1500 ml/h	@3000 ml/h
PID	1	2	3
Fuzzy	0	0	0

TABLE IV
ACCURACY EXAMINATION

Accuracy [g*s]	@300 ml/h	@1500 ml/h	@3000 ml/h
PID	-3	-1	2
Fuzzy	-395	-401	-401

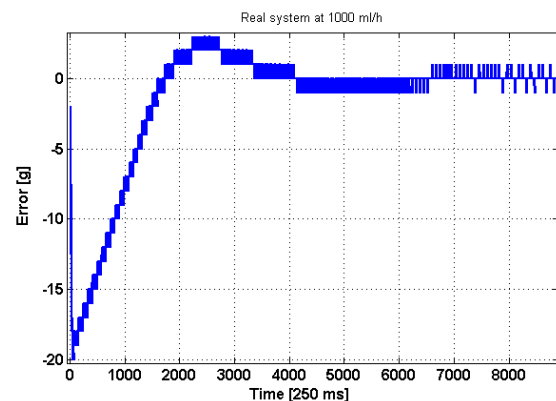
The error of the simulated system for both controllers can be seen in Fig. 5 (at 1500 ml/h flow rate), while Table III summarizes the results numerically.

It can be seen that the fuzzy controller was able to compensate the errors without overshoot; however, the overshoot of the PID controller can be accepted as well.

The accuracy of the controllers was measured based on the previously specified conditions, but the measured quantity was checked on an area under curve of a 200 second width window, after reaching the steady-state. The simulated system error for both controllers can be seen in Fig. 6 (at 3000 ml/h flow rate). Table IV summarizes the results numerically. It can be seen that the PID controller can really eliminate the residual steady-state error (Table IV). At the same time, the error of the fuzzy controller is about 400 g*s. Due to the fluid balance control of the patient and the medical solution transport the most important requirement of the peristaltic pump control is the elimination of residual steady-state error. Hence, this was the most important reason why we have chosen to implement the PID controller.

The stability of the system was checked with bigger errors than $\pm 1\%$. The swinging of the fluid bag was simulated with an added sine signal on the output of the plant. The amplitude of the sine wave was 10 ml, its frequency was 0.25 Hz. Bad tube segment was simulated with 30% slope error and with 100 ml offset error.

The performance of the controllers was acceptable in both cases, they did not induce instability. However, it has to be mentioned that with sine noise signal the expected transferred fluid volume was much more accurate with the PID controller. As a result, the PID controller (with the settings presented for the overshoot case) was applied to the real system (20 gram offset error). The response of the system can be seen on Fig. 7. It can be seen, that the desired control performance was achieved.

Figure 7. System error in the real system
(At 1000 ml/h, -5% slope error 20 g offset error)

IV. CONCLUSIONS

In this paper an automatic control solution of peristaltic pumps for hemodialysis machines was investigated. Parameter identification of the peristaltic pumps was examined with classical ARX, ARMAX, Box-Jenkins and state-space methods. Sufficient accuracy has been reached for all of the built-in models, but the best performance was reached with the state-space model.

PID and fuzzy controllers were designed for the identified system. They both accomplished the requirements, but due to faster control at low flow rates and higher accuracy PID controller proved to be the better choice that was also implemented and tested on a real system.

Further research will focus on tuning the soft-computing results [24], [25], but other modern control strategies as well focusing on robust optimization questions [26].

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