

Automation of an Extracorporeal Support System with Adaptive Fuzzy Controllers

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Abstract—For patients suffering from cardiogenic shock cardiopulmonary resuscitation may not be sufficient to restore normal heart function. However, their chances of survival may be increased with the use of an extracorporeal support system. With this system the patient's organs are perfused while being transported to the nearest hospital for proper treatment. In the automation of an extracorporeal support system the patient's vital signals are constantly monitored and proper adjustments are performed to improve organ perfusion. In this paper, an adaptive fuzzy controller is proposed that uses the knowledge and expertise of a perfusionist as a starting point and reference for regulation. Furthermore it is able to adapt to the patient's specific reactions by manipulating the rule base of the fuzzy controller. The performance of the adaptive fuzzy controller is tested with a simulation model of the cardiovascular system.

I. INTRODUCTION

The survival rate of patients after cardiac arrest, depends on how fast their blood circulation is restored. The longer the body remains without oxygen supply the lower are the chances of survival. For the cases of patients, suffering from cardiac arrest outside the hospital, immediate care will not be possible, cardiopulmonary resuscitation might not be sufficient and defibrillation might not provide effective circulation pump function. This may be followed by a vicious circle of low cardiac output, further myocardial ischemia and recurrent cardiac arrest. Proper treatment in these cases is only possible in the hospital [1], [2]. With the use of an extracorporeal support system (ECSS) it is possible to restore proper circulation, while being transported to the hospital for proper treatment [1], [3]. Under extracorporeal circulation it is crucial to provide adequate conditions for optimal organ perfusion, based on parameters such as mean arterial pressure (*MAP*) and extracorporeal flow rate (*EFR*).

In the operating room cardiopulmonary bypass is regularly used as a surgical procedure. A heart lung machine (HLM) is controlled by trained perfusionists, who, together with the surgeon evaluate the state of the patient and conduct adequate adjustments. Under emergency circumstances a perfusionist may not be at hand. However with the automation of the perfusion system this can be overcome. For the creation of the controller there are several challenges to be solved. The first one is the dependency of the different outputs,

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where the change of one variable will affect the output of another. For example, if the pump speed is increased to reach a specific pressure this will directly affect the blood flow and the oxygen delivery. Additionally the response of the patient will be non-linear, increasing the complexity of the system. Previous work has been done in the automation of the HLM. Misgeld et al. [5] developed a robust, self-tuning blood flow, without considering oxygen exchange. Fuzzy logic was considered as a control mechanism since it allows the creation of rules that can represent the actions of a perfusionist. Preliminary results were presented using fuzzy logic to control the centrifugal pump for the regulation of MAP and EFR [6]. The controllers worked independently and were able to reach the desired parameters, however it was only possible to reach either a target MAP or an EFR. In this paper we propose a fuzzy controller with an adaptive mechanism based on patient parameters and error evaluation. To test the proposed controller a simulation model of the cardiovascular system (CVS) together with oxygen exchange and medication is described. Afterwards the adaptive mechanism is explained and at the end we provide our results and conclusions.

II. SIMULATION MODEL

A. Cardiovascular System

The cardiovascular system is represented by a three compartment system that is separated into arteries, veins and capillaries. We assume that the heart is in cardiac arrest and the ECSS is fully in charge of restoring blood flow.

With this configuration it is possible to calculate the gas exchange produced in the capillaries with the absorption of oxygen and release of carbon dioxide. This was determined by the difference of the gas partial pressures [7] and its corresponding diffusion factor as shown in formula 3.

$$\frac{dC_{G,i}}{dt} = \frac{\dot{V}_B \cdot (c_{G,i} - c_{G,i+1}) - D_G \cdot (P_{G,i} - P_{G,i+1})}{V_i} \quad (1)$$

G represents oxygen or carbon dioxide respectively. $C_{G,i}$ defines the concentration of the gas in compartment i . \dot{V}_B is the flow, P the partial pressure and V stands for the total volume in the compartment.

B. Extracorporeal Support System

The ECSS is composed of a reservoir, a centrifugal pump, an oxygenator and a blood filter. Two compartments were used, one representing the reservoir and the other, the

oxygenator. The blood filter was defined as a resistance since its compliance is much lower than the compliance of the other components. The centrifugal pump was modeled as a constant head pump, based on the following formula:

$$H(Q) = \frac{\Delta P}{\rho \cdot g} + \frac{V^2}{2g} \quad (2)$$

H is total head of system dependant on the flow (Q), ΔP is the pressure drop between the inlet and the outlet of the pump (mmHg), and ρ is the density of the blood and g is the gravity. The change of pump head towards flow was obtained experimentally by generating different pump speeds and changing the resistance between the inlet and outlet.

The gas exchange in the oxygenator was modeled similar to the gas exchange within the capillaries with an additional gas compartment that is connected to an air-oxygen blender [4].

$$\frac{dP_G}{dt} = \frac{\dot{V}_G \cdot (P_{G,i} - P_G) + P_{atm} \cdot D_G \cdot (BloodP_{G,i} - P_G)}{V_G} \quad (3)$$

Arterial and venous cannulas are used to connect the ECSS with the patient. They are introduced in the arterial and femoral veins of the patient respectively. These were introduced into the model and their resistance characteristics were taken into account. From the arterial side a 20 Fr cannula was considered and from the venous side a 22 Fr cannula.

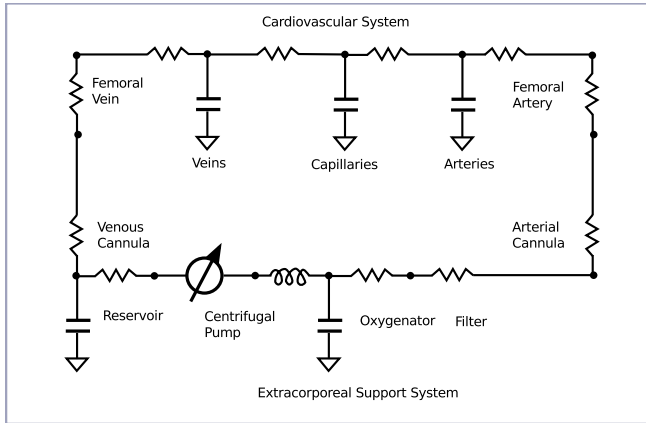


Fig. 1. Simulation Model

Figure 1 shows the simplified model of the ECSS together with the simplified CVS. To calculate the pressures and flow of each compartment formulas shown below were used.

$$\begin{aligned} p_i - p_{i+1} &= q_i R_i \\ p_i - p_{i+1} &= L \frac{dq_i}{dt} + R_i q_i \\ q_i - q_{i+1} &= C \frac{dp_i}{dt} \end{aligned} \quad (4)$$

C. Medication Model

Different vasoactive substances can be applied while the ECSS is in use. They aid in reaching the optimal physiological values of pressure and flow. The vasoactive drugs

were modeled in terms of different half-times and changes of vascular elements (resistance and compliance). For our research, Isosorbide Dinitrate (ISDN) was modeled as a vasodilator to decrease blood pressure while increasing flow and as vasoconstrictor Norepinephrine (NEP) was chosen for the contrary effect. Additionally, volume may be added to increase the overall pressure. The drug distribution in the body was modeled by calculating the concentration change in each compartment of the ECSS and the CVS. The drug elimination process was calculated from the concentrations within the capillary compartment. The medication effect was modeled depending on the concentration of each drug in the arteries multiplied by a constant gain factor.

III. CONTROL PARAMETERS

A. Patient Parameters

Specific patient parameters serve as input to the controller. The ideal control mechanism for the ECSS will establish the appropriate physiological values for best organ perfusion, providing oxygen and removing carbon dioxide. Taking this into account the main parameters that were considered for perfusion were the MAP, the EFR, oxygen saturation (SPO_2), and partial pressures of oxygen and carbon dioxide in arteries and veins ($PO_{2a,v}$ and $PCO_{2a,v}$).

It is difficult to determine the optimal value for perfusion since it will greatly depend on the characteristics of each patient. Previous research provides suggestions of what these values should be [8], [9]. As inputs height and weight of the patient are considered. These give an estimation of the body surface area, which is used to calculate the appropriate EFR. Additional preconditions of the patient are taken into account such as diabetes and pre-existing hypertension to determine the values of MAP. For each parameter a minimum and maximum value is considered. The controller will aim to maintain the patient's parameters within this range. If any of the values are surpassed the patient is considered to be at risk and an alarm is activated.

B. Output Parameters

The control parameters considered for automation were the following: centrifugal pump speed, fraction of inspired oxygen (FiO_2) and gas volume; regarding medication the dosages of ISDN and NEP are regulated and also the amount of infused volume.

Table I shows the input parameters with their minimum and maximum values together with the suggested target values. In the bottom part, the control outputs are shown.

IV. CONTROL

A. Fuzzy Control

The inputs of the controllers are the differences between the target value of the selected parameter and the actual value obtained from the patient.

Initially the perfusionist's knowledge is expressed as rules in simple, independent fuzzy controllers. For the input variables, only three fuzzy sets were used defined as low, normal and high. For the output variables five sets were used. This

Parameters to control				
Name	Min Value	Max Value	Target	Units
MAP	50	80	70	mmHg
EFR	2.3	3	2.5	L/m/m ²
SpO _{2a}	97	100	100	mmHg
PO _{2a}	80	200	100	mmHg
PCO _{2a}	10	60	40	mmHg
SpO _{2v}	73	80	76	mmHg
PO _{2v}	30	100	40	mmhg
PCO _{2v}	10	60	46	mmhg
Outputs				
Pump speed	0	3900	-	rpm
FiO ₂	20	100	-	%
Gas Vol	0	10	-	L/min
ISDN	0	2	-	ug/kg/min
NEP	0	0.1	-	ug/kg/min
VOL	0	0.1	-	ml/kg/min

TABLE I
CONTROL PARAMETERS

reduces significantly the amount of rules needed to be set up by the perfusionist. These controllers are referred to as perfusionist controllers.

In total, five fuzzy controllers were used to express the perfusionist's knowledge. Each expresses the rules to control one parameter, MAP, EFR, medication, FiO₂, or gas volume. The MAP and EFR controllers were based on a Fuzzy-PI controller [10], where the tendencies of each input were included to improve response. These controllers give as output the increase or decrease of pump speed. From these outputs the mean value is calculated to form only one control value.

The parameters of gas exchange are obtained in practice with the use of a gas analyzer, in this case a CDI500 from Terumo[11]. This device may only obtain values every 6 seconds, so the outputs of FiO₂ and Gas Volume in simulation were evaluated every 6 seconds. The MAP and EFR are evaluated every second.

B. Adaptive Control

To combine the knowledge of the perfusionist and the actual reaction of the patient, additional controllers are used. For each of the output control variables in table I, an adaptive controller is implemented. The adaptive controller starts with an empty rule set. It uses the same inputs as the according perfusionist controller, plus additional derivatives of each of the input parameters. For the fuzzification of inputs and outputs the variables of the controller work in the range from -1 to 1, and real values are introduced with the use of gains. Figure 2 shows a fuzzy controller with two inputs, and an output with its corresponding gain.

Each input and output variable is expressed with seven triangular sets of equal size. They are distributed to cover the complete range.

The adaptive mechanism is described in the following steps:

- 1) For each parameter the error (difference between current value and target) and its derivative are calculated.

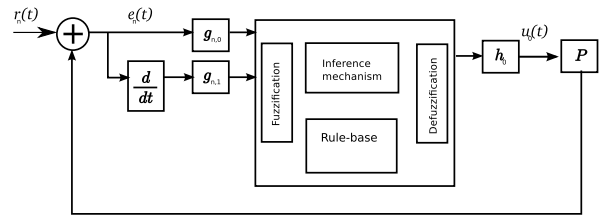


Fig. 2. Fuzzy Controller with input and output gains

- 2) The mean square error (MSE) of the input parameters is calculated with the following formula:

$$MSE = \sum_{i=0}^{numParam} (v_i - t_i)^2 \quad (5)$$

v_i is the current value of parameter i and t_i is the corresponding target value.

- 3) The perfusionist controllers are evaluated to generate their corresponding output values.
- 4) The output of the perfusionist controller plus the inputs of the controller are used as training data for the adaptive controller.
- 5) The adaptive controller checks, if new rules need to be created according to the training data. This is done by first obtaining the active sets from the inputs and outputs. If a rule exists with these sets and its truth is above a predefined threshold no new rule needs to be created, otherwise a rule is created and a weight of one is assigned to this rule.
- 6) The output of the adaptive controller is calculated and the rule with maximum truth used is stored in a rule list.
- 7) The output obtained is summed to the current output control value and applied to the ECSS considering not to exceed its minimum and maximum range.
- 8) After a predefined delay the MSE, previously calculated, is analyzed together with the rule, stored in the rule list at $t - delay$. If the MSE is decreasing this rule's weight is increased. If the MSE is increasing the rule's weight is decreased.
- 9) All the rule weights in the adaptive controller are checked and if they reach a negative weight they are eliminated from the rule set.

Figure 3 shows an example of the adaptive controller concerning in this case, showing the pump speed control.

V. IMPLEMENTATION

The simulation models were created using a mathematical model language (MML) that can be evaluated in JSim. The adaptive control was programmed in C++. The connection between the simulation and the controller is done with a small server with communication messages. Additional information may be found at [6].

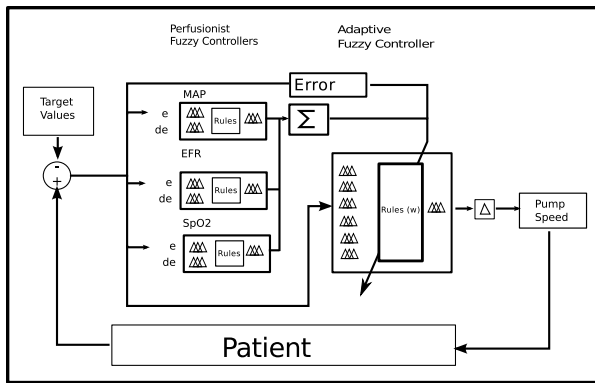


Fig. 3. Adaptive fuzzy controller for pump speed control

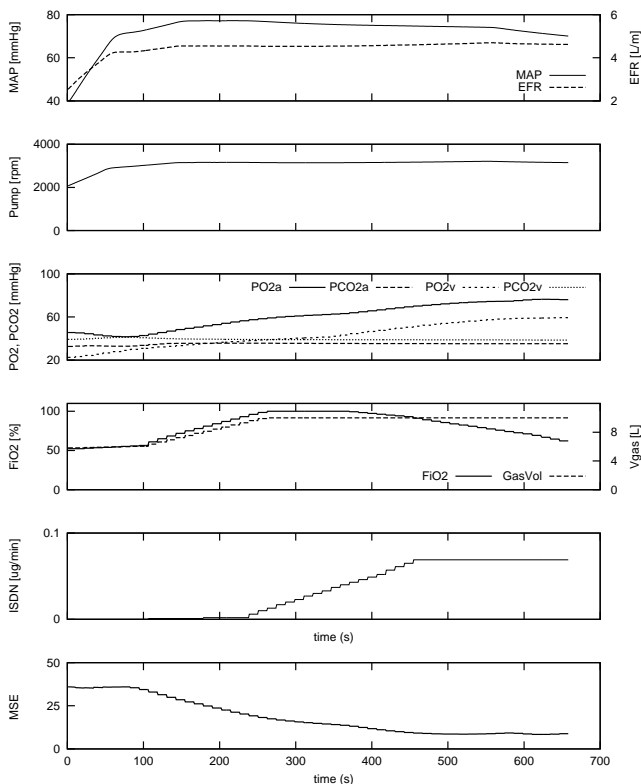


Fig. 4. Simulation Results

VI. RESULTS

The simulation model was set to have the HLM connected to the patient at an initial state with a pump speed of 2000 rpm. The FiO_2 is set to 50 % and an initial Gas Volume was set to 5 L/m. From these settings the controller was activated to obtain the target values previously suggested in table I

The controller first restored the values of MAP and EFR, the value of pressure was slightly higher than the target value and the EFR was lower so the effect of a vasodilator (ISDN) was used by the controller to compensate this difference and reach the desired targets. To reach the target values of gas exchange the FiO_2 was initially increased to 100%. Afterwards this parameter is gradually reduced. From the MSE we can

observe that the error throughout the simulation was reduced. It will not fully be eliminated since the gas exchange values are not exactly at their target values. However the patient's vital signals are restored to parameters that are considered to provide good organ perfusion.

VII. CONCLUSION

Extracorporeal support may be of great help to people who suffer a heart attack outside the hospital. To ensure this, optimal perfusion must be guaranteed at all times. Since experienced personnel may not always be on hand automation is essential. Fuzzy logic provided a straight forward solution to implement the knowledge of the perfusionist, however further adaptation is necessary to improve the controller's behavior according to the needs of each individual patient. Still the controller's complexity is not elevated and it is possible to extract in a comprehensible way, which rules were taken into account. Initial results show that the system is able to evaluate, if the actions taken are improving the patient's state and if not make the correct adjustments, however further cases need to be analyzed to assure the correct adaptation for different settings.

VIII. ACKNOWLEDGMENTS

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