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SIMULATION OF EXTRACORPORAL CIRCULATION FOR THE DESIGN OF A FUZZY CONTROLLED PERFUSION

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ABSTRACT

A simulation environment was developed as a tool for the design of a fuzzy controlled perfusion. This consists of a mathematical model of the cardiovascular system connected to a heart-lung machine. An existing cardiovascular model extracted from the PHYSIOME database was used and extended with the model of a HLM. A visual interface was created to simulate real-time patient data where specific scenarios can be evaluated. Preliminary results are shown where the model was adjusted with experimental data and a fuzzy controller was activated to test its performance.

KEY WORDS
Simulation, Extracorporal Circulation, Fuzzy Control

1 Introduction

Today, the use of a heart-lung machine (HLM) is a safe and routinely used technique in cardiac surgery. Currently the HLM is operated by perfusionists in cooperation with anesthesiologists and heart surgeons in the operating room. Outside the hospital patients suffering from cardiogenic shock would benefit with an early application of a portable extra-corporal circulatory support system (ECSS) preventing multi organ failure. This however requires the presence and constant supervision of the patient by trained personal at the emergency site. With the automation of a portable ECSS optimal perfusion may be achieved with minimal workload for the human operator.

The complexity involved in the design of a controller for a medical device is considerably high since the reactions of each patient may be different from one another, additionally a controller must be robust and fault tolerant where patient security is of mayor concern. In the development and design of a controller intensive tests are needed to eliminate possible errors, test the reliability of the resulting controller and evaluate its behavior to different scenarios. Experiments using animal models will not be sufficient to cover all of the possible scenarios that may happen in a real situation. For these reasons the focus of this project is to design a simulation environment capable of recreating the behavior of the cardiovascular system (CVS) connected to an ECSS. This allows the recreation of specific scenarios that may be executed numerous times allowing intensive error checking and optimization.

Fuzzy logic was considered as a control method since it gives the possibility of translating the experience of doctors to rules that can be applied by the controller. The fuzzy controller was connected to the cardiovascular model via a network interface.

With a simulation environment the designed controller may be evaluated over different scenarios and will allow the validation of the controller to work effectively by making similar decisions of a trained specialist.

2 Model and Methods

2.1 Cardiovascular Model

Extensive research has been done in the mathematical modeling of the human cardiovascular system [1, 2, 3, 4]. For this project a model obtained from the Physiome database was used [5]. A closed loop cardiopulmonary system was selected composed of a four-chamber varying-elastance heart, a pericardium, a systemic circulation, and a pulmonary circulation. This model was compiled by Maxwell Neal. More details about this model maybe found at [2, 6]. A Mathematical Modeling Language (MML) is used to describe the model which is then compiled and executed by the simulation system called JSim. This system is part of the Physiome Project.

2.2 Heart Lung Machine Model

For the HLM the Lifebridge B_2T system was used as a reference. It is a portable, modular and easy-to-use ECSS, designed to be applied in emergency transportation or resuscitation [7].

The Lifebridge HLM is represented by models of its main components: a reservoir, a centrifugal pump, an oxygenator, a filter, tubing, and cannulation that connects to the body. From these components the relation between the difference in pressure (ΔP_i) of the input and output and the flow (Q) was extracted. This was modeled using a quadratic equation with two constants (Ca_i,Cb_i):

$$\Delta P_i = Ca_i Q^2 + Cb_i Q \qquad (1)$$

Experiments were done to extract the constants of each component, obtaining the parameters in table 1.

Table 1
HLM parameters

i	Name	Ca_i	Cb_i
1	Pump Resistance	1.4	6
2	Reservoir	0.01	0.1
3	Oxygenator	0.8	12
4	Filter	0.7	3
5	Tubing	0	25
6	Venous Cannula	2.8	10
7	Arterial Cannula	3.8	6

The centrifugal pump was modeled based on the assumption that the pump generates a constant head which depending on the output resistance can be converted to flow and pressure. This is expressed in equation 2.

$$H = \frac{\sum_{i=1}^{7} \Delta P_i}{\rho g} + \frac{\Delta P_{CVM}}{\rho g} + \frac{V^2}{2g} \qquad (2)$$

H represents the total head developed by the pump in meters. ΔP_i is the difference in pressure between the inlet and the outlet of the pump and other components that compose the extra-corporal circuit. ΔP_{CVM} is the difference in pressure from the cardiovascular model. ρ is the density of blood ($1060 kg/m3$)[8], g is gravity ($9.81 m/s^2$). V is the velocity at the outlet of the pump (m/s).

The velocity is converted into flow (Q) using equation 3 where the outlet area of the pump is considered (A) ($7.85 * 10^{-5} m^2$).

$$V = Q/A \qquad (3)$$

A decrement of H is considered depending on the flow going through the system. Two variables ($Pump_S$ and $Pump_D$) were used for this purpose. These variables change depending on the speed at which the pump is running (RPM).

$$H = Pump_S(RPM) - Pump_D(RPM) * Q \qquad (4)$$

$$Pump_D = PumpC_1 * RPM + PumpC_2 \qquad (5)$$

$$Pump_S = PumpC_3 * RPM + PumpC_4 \qquad (6)$$

The pump speed range is from 0 to 3900 RPM. The pump constants are expressed in table 2.

Table 2
Pump parameters

Name	Value
$PumpC_1$	$7.8x10^{-5}$
$PumpC_2$	$2.2x10^{-2}$
$PumpC_3$	$2.5526x10^{-3}$
$PumpC_4$	-2.7

Replacing the previous equations we have the following formula:

$$Pump_S(RPM) - Pump_D(RPM) * Q = \frac{\sum_{i=1}^{7} Ca_i Q^2 + \sum_{i=1}^{7} Cb_i Q}{\rho g} + \frac{\Delta P_{CVM}}{\rho g} + \frac{(Q/A)^2}{2g}$$

This gives the resulting quadratic equation:

$$Pump_S(RPM) - \frac{\Delta P_{CVM}}{\rho g} = \left(\frac{\sum_{i=1}^{7} Ca_i}{\rho g} + \frac{1}{2A^2 g} \right) Q^2 + \left(\frac{\sum_{i=1}^{7} Cb_i}{\rho g} - Pump_D(RPM) \right) Q$$

This equation was introduced into the JSim environment and added to the cardiovascular model. After calculating the resulting flow the pressures of each component where calculated to be compared with the pressures obtained from the experimental data.

2.3 Connection of Cardiovascular Model to the HLM

The CVM obtained from the Physiome database was modified to connect the model of a HLM. In the systemic circulation the Resistance of the Systemic Arteries (Rsa) was divided in two. In between a resistance for the femoral arteries was placed (Rfa) to connect to the arterial cannula resistance (ArtC) from the HLM. From the venous side the resistance of the systemic veins (Rsv) was divided and connected to a resistance representing the femoral veins (Rfv). From this resistance the venous cannula (VenC) was connected. This is shown in Figure 1.

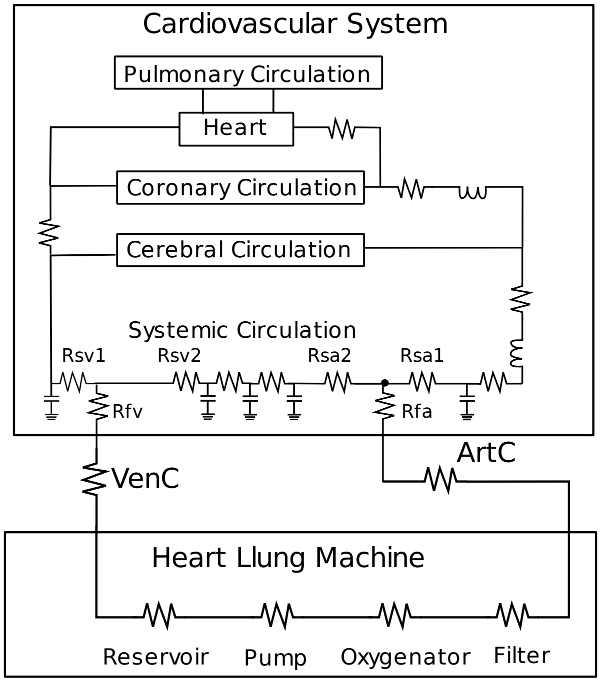


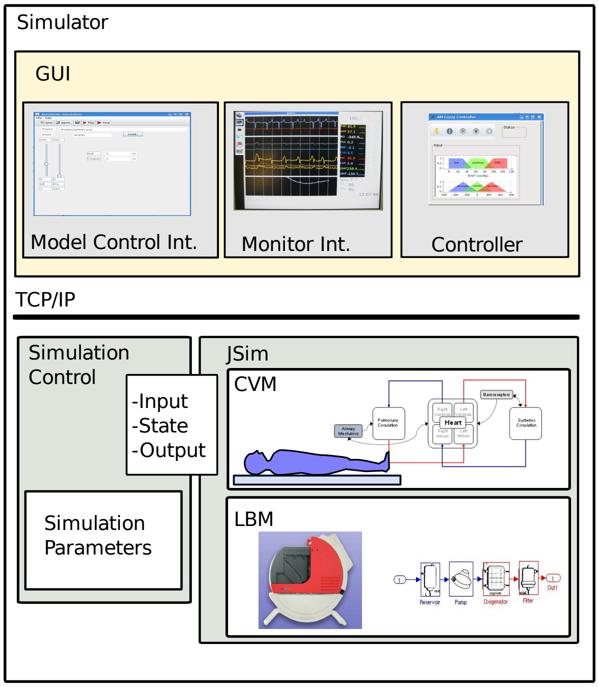
Figure 1. Connection between CVM and HLM

2.4 Fuzzy Control

We used a standard fuzzy system with Mamdani inference to control the pump speed of the HLM. In a first approach the input parameter to the control loop was the MAP together with the flow from the HLM. For the input variables 3 sets are defined, labeled as low, medium and high. The controller output is a correction factor of the current pump speed. Rules were created using these sets with the help of medical doctors to describe a good perfusion.
The controller operates at 1 Hz, that means every second the current MAP and flow is obtained and a new pump speed is set accordingly. More information regarding the fuzzy controller may be found at [9].

2.5 Simulation Environment

A simulation control program was created for loading the initial parameters of the model, the state variables, control variables and outputs to be used for monitoring and control. This program connects to a server in charge of sending the simulated data to the other programs. Through a model control interface the different parameters can be changed before starting the simulation. A monitor interface is used to show the results of the model in the same way as during experiments. The fuzzy controller receives the output of the simulation and sends back to the simulator the control output. A block diagram of the different components is shown in Figure 2.



CVM - CardioVascular M odel
LBM - Lifebridge Mod el

Figure 2. Simulation Environment

2.6 Experimental data

Animal experiments were conducted using ordinary pigs of approximately 80 kg. From these experiments pressure parameters among with blood flow, SpO2 and ECG were captured and recorded. This was done using AutoMedic a designed platform developed specifically for this project. More details of this platform may be found at [10]. Initial results from this experiments may be found in [10, 9]. During the animal experiments the effects of vasoconstriction and vasodilation were evaluated. During these tests a fuzzy controller was activated to control the pump speed and regulate the flow and MAP.

2.7 Model adjustments

From the experimental data the simulation model was adjusted to represent the same behavior by modifying the input and output resistances from the HLM together with the systemic vascular resistances (Rsa, Rfa,Rsv and Rfv) of the cardiovascular model. This was done considering reference values at different RPMs. After these adjustments the resistances remained constant trough out the simulation.

3 Results

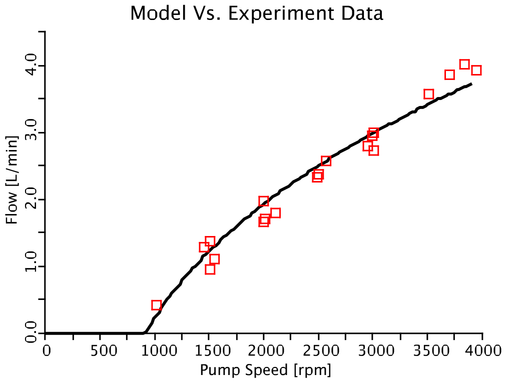


Figure 3. Simulation Results

Figure 3 shows the relation between the pump speed and the flow generated by the HLM resulting from the constructed model (black line). These results were compared with the experiment data shown in red squares. From this results we can notice a good correlation. The model was set to generate flow only after 900 RPM. At the highest speed the experiment data shows a slightly higher flow rate compared to the flow generated by the model.

From figure 4 we can observe the results from an animal experiments during vasoconstriction after delivering arterenol. Some artifacts are noticed in the MAP however the general behavior of increased pressure is noticed. This also affected the heart rate. The HLM was connected to the fuzzy controller and reduced the pump speed when the MAP was too high. This same behavior was produced in the simulation environment by increasing the heart rate and the resistances from the systemic arteries, also connecting the model to the fuzzy controller. Figure 5 shows the result of this simulation.

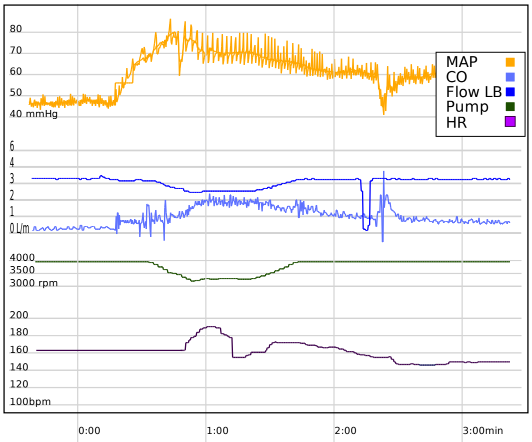


Figure 4. Experiment Results (Vasocnstriction)

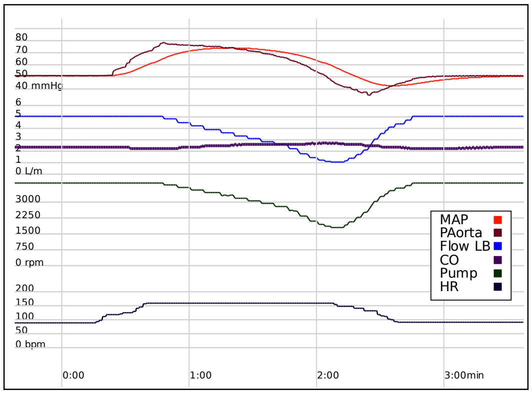


Figure 5. Simulation Results (Vasoconstriction)

4 Discussion

Being able to simulate in a virtual environment is crucial in the design of a controller. It enables engineers to test the implemented software for software and hardware errors. For the design of the fuzzy controller it gives an insight of the rules that may be used. Additionally with the use of this simulation environment the need of animal experiments is greatly reduced giving the possibility to do intensive tests.

Several models of the cardiovascular system already exist. These models where analyzed in terms of easy implementation and capability to represent the experimental data. The model provided by the physiome database was easy to use with JSim and could be extended to the purposes of this project.

From the simulation and experimental results we see that both have comparable results. Further work is needed to provide a way to recreate different scenarios enabling specialized doctors to transmit their knowledge of an optimal perfusion under different circumstances. This will require the creation of a controller that is capable to adapt to the specific needs of the patient. The use of fuzzy control may allow this adaptability while still being able to understand the general structure of the controller and the rules that are being used.

The current model can be extended with the calculation of the heart rate given by a model of the baroreceptors and oxygen exchange allowing the control of other variables and the interaction between them.

Additional work is needed to be able to recreate possible errors caused by the sensors used in a real situation. This involves the creation of different mechanisms to prevent the controller from making the wrong decisions.

5 Conclusion

Computers have become fundamental in the medical domain creating a whole new field of health informatics. Implementing user interfaces allows medical doctors to visualize a virtual setup where scenarios representing real life situations can be simulated. This can be run a large number of times until the best way to proceed is considered to be established. This may considerably decrease the time needed to design a robust controller.

In the current work we show a cardiovascular model capable of creating a pulsatile heart perfusion interacting with a heart-lung machine of non pulsatile flow. A fuzzy controller is capable of regulating the flow and pressure of the system for an optimal perfusion. This controller will be extended to adapt to specific patient characteristics. Further work is needed to extend the current model to integrate baroreceptors for heart rate regulation and oxygen exchange. This will enable the simulation of other control signals additional to the pump speed of the HLM including oxygen concentration from the oxygenator.

With the use of this simulation environment it is possible to rectify and validate the correct operation of the controller to different situations bringing it a step closer to a real implementation.

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