A STATE-OBSERVER FOR PATIENT STATUS IN CARDIAC SURGERY

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Abstract-**Today, control of extracorporeal perfusion – the standard technique in cardiac surgery - is achieved by perfusionists making short-term decisions based on their clinical experience and on data collected pre- and intraoperatively. But in spite of extensive monitoring postoperative complications occur which most probably are due to unrecognized complications during surgery. By extending monitoring towards the perfusion status of important inner organs and the patient's metabolic status, the assessment of the actual patient situation could be improved. Thus, the adaptation of extracorporeal circulation to the patient's needs would become possible. As these parameters normally cannot be measured, we propose a system similar to a state-observer capable of calculating them.**

***Keywords* - Extracorporeal circulation, cardiac surgery, state-observer, modeling, cardiovascular system**

I. Introduction

Cardiac surgery, especially coronary artery bypass grafting and valve replacements, is frequently performed in the industrialized countries. These operations generally require a high monitoring effort in order to protect the patient during the unphysiological situation of extracorporeal circulation. Today, mortality in cardiac surgery is generally below 5%, in coronary revascularization even below 3%. But often postoperative complications, especially neurological defects occur which most probably can be attributed to unrecognized complications during surgery. Important patient parameters such as brain perfusion cannot be measured. Others like blood gases and pH are measured in intervals of 15 – 30 minutes only because a time-consuming laboratory blood analysis is necessary.

Extending and improving patient monitoring during cardiac surgery and thus enabling the short-time adaptation of extracorporeal circulation to the actual demands of the individual patient is considered as an important goal in perfusion science for the next few years. Dynamic modelling of human circulation during extracorporeal circulation and the application of control theory methods can offer vital non-measurable information in real-time. Suitable state-observers or estimation algorithms can calculate patient parameters and thus improve the quality of patient monitoring during cardiac surgery considerably.

In this paper, we propose a mathematical model of extracorporeal circulation which is able to simulate different perfusion regimens and which takes into account the individual properties of any particular patient. This model can provide essential information of changes taking place during cardiopulmonary bypass, and display the actual haemodynamic and metabolic situation that can be expected under different perfusion regimens. Furthermore, we present a system similar to a state-observer that is able to predict important patient parameters in short intervals.

II. Methodology

Standard monitoring includes continuous measurement and display of hemodynamic parameters such as arterial pressure in the A. radialis, central venous pressure, pump flow rate and body temperature. Furthermore, discontinuous measurement of metabolic parameters such as blood gases, pH and plasma electrolyte concentrations is carried out in intervals of 15 – 30 minutes. For a better assessment of the actual patient status an extended monitoring including the actual perfusion status of important inner organs such as brain, kidneys, liver or intestines and continuous monitoring of metabolic parameters is necessary. These parameters could be provided by using a mathematical model of the human circulatory system under extracorporeal circulation conditions as an estimator or a 'state'-observer.

The model considers the human circulatory system under system-theoretic aspects. It has been realised using the MATLAB toolbox SIMULINK and can be divided into three main parts (see fig. 1):

- circulatory dynamics, with the heart and the pulmonary vessels excluded from the circulation because of cardiopulmonary bypass,
- control mechanisms of the circulatory system such as the autonomic nervous system, the renin-angiotensin system, autoregulation of blood flow in the brain and in the kidneys and local metabolic control, and
- physiologic subsystems influencing circulation dynamics (such as the respiratory system, the kidneys, electrolyte and water balances etc.).

Furthermore, individual patient conditions such as hypertension or renal insufficiency can be taken into consideration during a simulation.

A. Circulatory Dynamics

The block *Circulatory Dynamics* is the core of the model. This block represents the basic hemodynamics of the circulatory system. The subsystem *Systemic Arteries* contains a multi-segment branching structure consisting of 128 segments arranged according to the anatomical architecture of the human arterial tree. This representation includes all the central vessels and principal arteries supplying the extremities with each segment having anatomically correct

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Abstract

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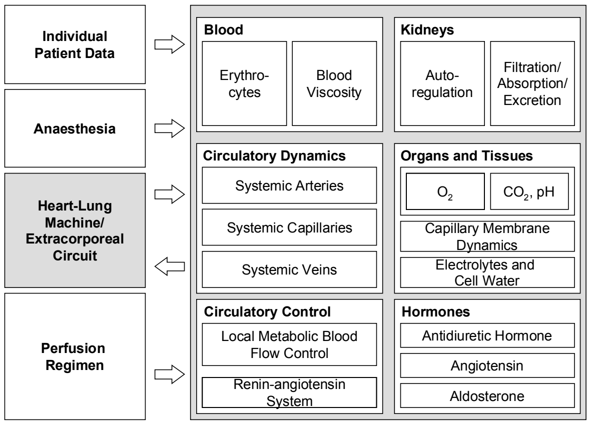

Fig. 1. The model of the human circulatory system under extracorporeal circulation

dimensions and elastic properties [1]. Peripheral branches are terminated by a resistance term representing smaller vessels like arterioles and capillaries. Blood flow and pressure are expressed by the intensity of current and voltage in an electrical analogue based on the Navier-Stokes equations for fluid flow in elastic tubes. Resistance, inductivity, and capacitance are implemented according to the physical properties of the arterial tree and the rheology of the blood.

$$p_{k-1} - p_k = \frac{9\rho l}{4\pi^2}\frac{dq_k}{dt} + \frac{8\eta l}{\pi r^4} q_k = L\frac{dq_k}{dt} + Rq_k \tag{1}$$

$$q_k - q_{k+1} = \frac{3\pi r^3 l}{2Ed}\frac{dp_k}{dt} = C\frac{dp_k}{dt} \tag{2}$$

Equations (1) and (2) are difference-differential equations linking flow and pressure with terms of resistance (R), inductance (L), and capacitance (C); k is the segment number, l is the vessel length, E is Young's modulus, ρ is blood density, η is blood viscosity, r is the vessel radius, d is the thickness of the vessel wall, p is blood pressure, q is blood flow and t is time. During a simulation, the terminal resistance of each segment can be influenced by the renin-angiotensin system and by local metabolic control.

B. Extracorporeal Circulation

Cardiac surgery generally requires a resting, bloodless heart. But as vital functions - oxygen and nutrient delivery to the cells and removal of CO_2 and metabolites - are based on the circulation of blood the circulation has to be maintained during surgery. This is achieved by means of a technique called cardiopulmonary bypass or extracorporeal circulation. The central component of this technique is the heart-lung machine replacing the heart and the lungs which are excluded from the circulation during surgery. Besides these changes in the 'set-up' of the circulation, there are several other factors influencing haemodynamics and metabolic status during extracorporeal circulation that have to be integrated into the model [2][3]. First of all, the perfusion regimen can differ with regard to flow characteristics (pulsatile/nonpulsatile perfusion), pump flow rate (low-flow/high-flow perfusion) and acid-base management (pH-stat/alpha-stat). Other factors related to the installation of extracorporeal circulation are haemodilution, cardioplegia (deactivation of the heart), hypothermia, and hemolysis caused by the contact of the blood to the artificial surfaces of the extracorporeal circuit. Furthermore, the effects of anesthesia [4] and the patient's disease exert an influence on the patient status during cardiopulmonary bypass and have to be considered during simulation.

In fig. 2 the human circulatory system under standard cardiopulmonary bypass conditions is considered under system-theoretic aspects and depicted as a block diagram. In terms of control theory the human circulation is the controlled system. The parameters measured during the surgical intervention are compared to pathophysiological set values by the perfusionist. He can be regarded as a controller as he also operates the heart-lung machine, the actuator by means of which the control strategy is transmitted to the controlled system, i. e. the human circulatory system.

C. State-Observer

An important feature of the computer model described above is its ability to simulate the pulsatile characteristics of blood pressure and flow. In addition, it provides a high resolution for blood pressure and flow not only in time but also in location, especially within the systemic arterial tree. This is required for the estimation of brain perfusion or perfusion of other inner organs.

The Luenberger observer (see fig. 3) serves as the basic concept for the observer presented in this paper. An essential part of this observer is a model of the controlled system that receives the same input parameters as the controlled system itself. This model estimates state variables and output parameters of the controlled system. The estimate error, i. e. the difference between the measured output parameters and the estimated output parameters, is fed into a feedback loop containing a correcting element for adapting the model so that the estimate error is minimized. [5][6].

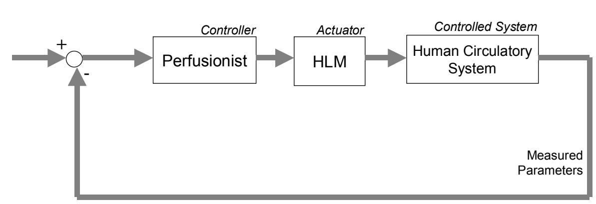

Fig. 2. Extracorporeal circulation as a feedback control system

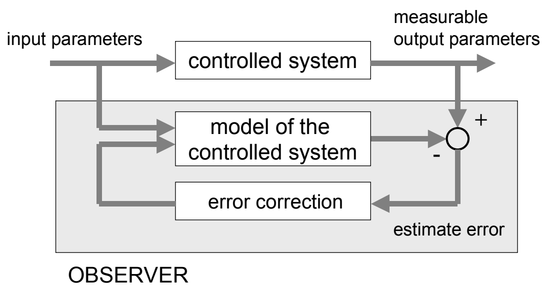

Fig. 3: The concept of a state-observer (Luenberger observer)

Because of the nonlinearities and the high complexity of the model classical design methods for state-observers are not applicable. Nevertheless, by periodically matching the calculations of the model with measured parameters a system similar to a state-observer is formed. Examples for matching data are arterial pressure or the results obtained from laboratory blood analysis.

Because of the heterogeneity of the parameters that are to be observed – hemodynamic parameters as blood pressure and flow in different inner organs on the one hand and metabolic parameters such as partial oxygen pressure, partial carbon dioxide pressure or pH on the other hand – for each parameter an own adaptation algorithm had to be developed. The resulting system structure is depicted in fig. 4.

A suitable parameter for matching estimated with measured data is the arterial pressure in the A. radialis. This parameter is monitored continuously during a cardiac operation. If only small deviations between estimated pressure and measured pressure occur, it can be assumed that blood pressure in the other vessels such as A. carotis (brain perfusion) or A. renalis (kidney perfusion) are well approximated. The error correction is realized by adapting the terminal resistances representing arterioles and capillaries (see section II.A).

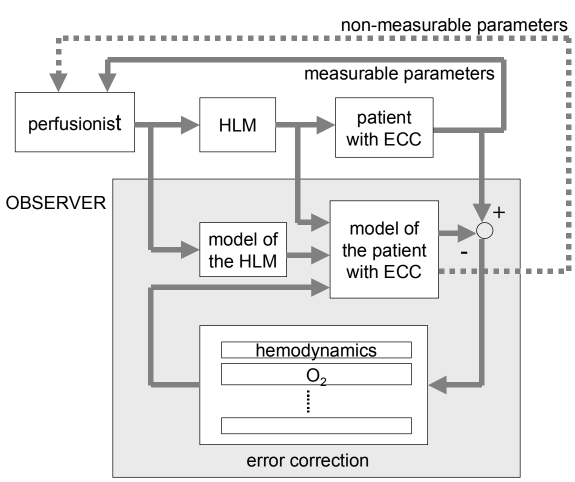

Fig. 4: Schematic representation of the observer, integrated in the standard ECC setup

III. Results

Fig. 5 shows the estimate of the state-observer for the blood pressure in the A. radialis compared to a hypothetical pressure curve. This hypothetical pressure curve has been designed in order to examine the reaction of the state-observer to stepwise changes in measured pressure data. As it can be seen in fig. 5a, the state-observer is capable of approximating the given reference data except for a short transitional period after each step.

In fig. 5b the estimate error for the system described above is depicted. Apart from the transitional periods, the absolute error is very small.

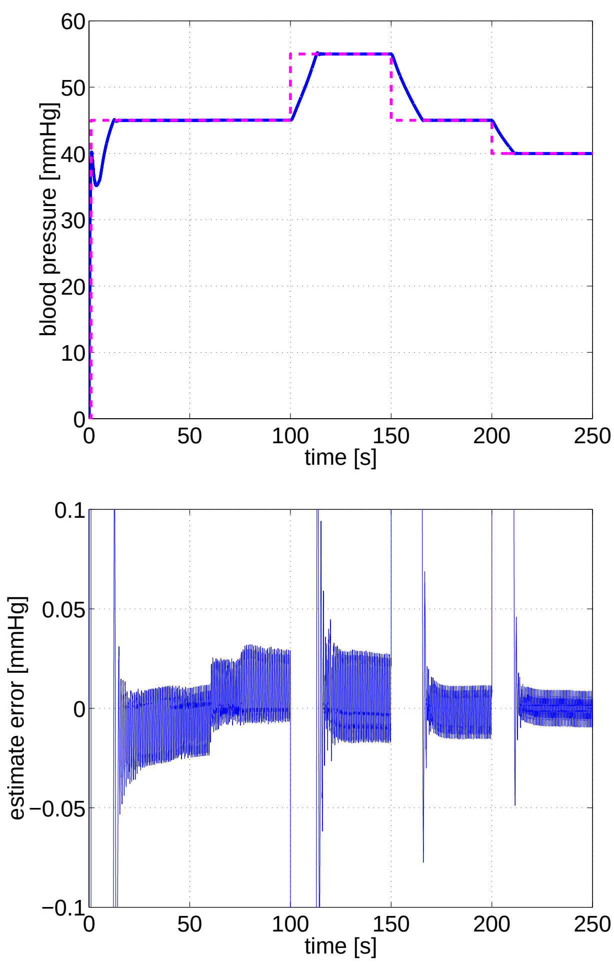

Fig. 5: a) Blood pressure in the A. radialis – Comparison of a hypothetical pressure curve (dashed line), serving as an example for measured data, with estimated pressure data from the state-observer (solid line)
b) Estimate error, i. e. the difference between the hypothetical pressure curve and the estimated pressure data from the state observer

Fig. 6 shows the estimate of the state-observer for the blood pressure in the A. radialis in comparison to measured data from the A. radialis. These measured data are cut out of a data registration file that was generated automatically during a heart operation for documentation purposes. After the settling process of the system the measured data is well approximated by the state-observer.

This becomes even more obvious by looking at the estimate error (fig. 6b). When there are changes in the gradient of the measured data as for example at t=60 s where the gradient changes from negative to positive values, the estimate error is slightly increased for a short period of time but decreases quickly again.

IV. Discussion

As it can be seen in the simulation results (fig. 5 and 6) the state-observer is capable of approximating the measured data well, except for settling process at the beginning of the simulation and transitional periods occurring after stepwise changes of the reference data.

During the transitional periods after stepwise changes of the reference data, the observer shows a monotonous approximation towards the reference data. The transitional periods may possibly be shortened by choosing an error correction algorithm that results in an oscillatory behavior as a response to stepwise changes of the reference data. But this approach bears the risk that the whole system becomes unstable. Thus, the error correction algorithm with the monotonous response has been preferred.

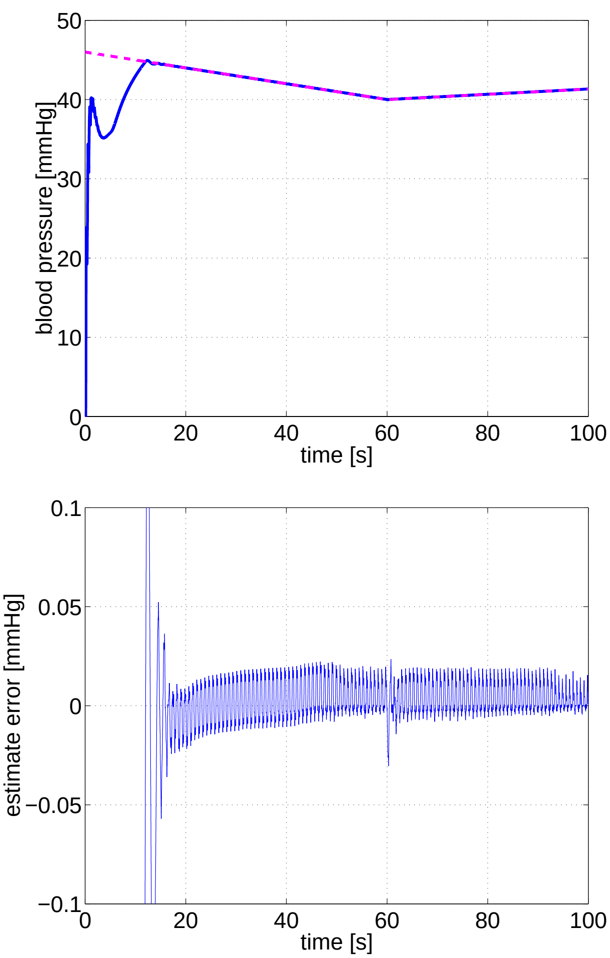

Fig. 6: a) Blood pressure in the A. radialis – Comparison of estimated data from the state-observer (solid line) with measured data from a heart operation (dashed line)
b) Estimate error, i. e. the difference between the measured data and the estimated data from the state observer

V. Conclusion

The model of the human circulatory system described above incorporates the effects of extracorporeal circulation. Differences in perfusion regimens related to flow characteristics, pump flow rate and acid-base management and their effects on the distribution of blood volume, hemodynamics and metabolic status can be simulated

The model proved to produce realistic simulation results which are consistent to clinical data. Therefore, it can be used for the derivation of a state-observer that provides estimates of hemodynamic parameters such as blood pressure and flow in important inner organs on the one hand and metabolic parameters such as blood gases, pH and electrolytes during the intervals between laboratory blood analyses on the other hand.

This system is able to supplement the existing monitoring devices in the operating theatre and thus to enhance the quality of patient monitoring considerably.

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