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„Robust Multivariable Blood-Gas Control for Extracorporeal Circulation with Heart-Lung Machine Support“

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Robust Multivariable Blood-Gas Control for Extracorporeal Circulation with Heart-Lung Machine Support

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Introduction

During extracorporeal circulation (ECC) with heart-lung machine (HLM) support, the HLM guarantees the function of the human heart and lung, which is up to day manually operated. Addition of oxygen and removal carbon dioxide is applied to the withdrawn venous blood by the oxygenator, an artificial lung. Today, membrane oxygenators are used in a cardiovascular operation and streamed with a nitrogen/oxygen gas mixture in order to control the arterial partial blood-gas pressures oxygen (pO_2) and carbon dioxide (pCO_2). In a HLM standard procedure, pO_2 and pCO_2 are controlled with the input values oxygen fraction in the gas and total gas flow, respectively [1]. Fig 1 shows the principle inputs, components and outputs of the blood-gas control of a HLM. It can be clearly seen that the process is a two-input, two-output process. For the control design coupling occurs and should be regarded.

The automatic control of blood-gases was presented in [2], where single-input-single-output controllers where designed and checked for robustness. In this approach, a multivariable robust controller is designed via the H_∞-loop-shaping approach.

System modelling and control

System modelling

The plant to be controlled consists of the gas blender, the oxygenator and the blood-gas analyser. The gas-blender was modelled as a first-order PT1-process for both, oxygen fraction in the gas (FiO_2) and gas-flow q_g. This results from the dynamics of the gas-mixer valves. An additional time-delay has to be incorporated for the oxygen fraction in the gas (transport from gas mixer to oxygenator) and varies with gas flow. Uncertainties in the input functions are due to gas leaking though the valves and are incorporated to the control design. The exchange of gases in the membrane oxygenator was modelled by a 11-compartment model, which describes the diffusion processes across the membrane and was adapted from a physiological lung model [3]. The model is highly nonlinear, parametrised with physiological values/diffusion capacities and depends on blood-flow and venous conditions, which can be seen as process disturbances. The blood-gas analyser is described by first order PT1-process dynamics, a time-delay resulting from discretisation and a quantisation of 1 mmHg. The parameters and devices are described in detail in [2].

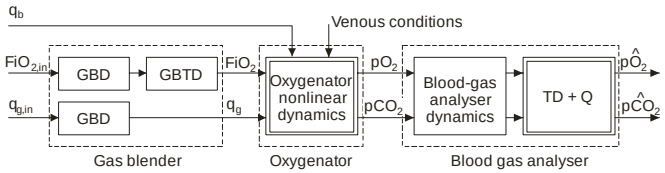

Fig 1 Blood-gas exchange process model used for simulation and control design (GBD: Gas-blender dynamics, GBTD: Gas-blender dynamics + time-delay, TD + Q: Time-delay and quantisation)

Model linearisation and controller design

An input output linearisation was applied to the oxygen exchange dynamics of the plant [4]. A block diagram of the control structure is given in Fig 2 and shows the linearisation feedback $\Psi(\cdot)$, for which the full-state vector is needed. The process dynamics for the blood-gas exchange (oxygenator) with applied input-output-linearisation for the oxygen process (FiO_2 to pO_2) was then estimated at certain operating points. The process was stimulated with input impulses and process models were estimated with the System Identification Toolbox (The Mathworks, Natick, Massachusetts (USA)) to

$$\mathbf{G}_p(s) = \begin{bmatrix} \dfrac{K_{p,11}(T_{z,11}s+1)}{(T_{w,11}{}^2 s^2 + 2\zeta_{11}T_{w,11}+1)(T_{11}s+1)} & \dfrac{K_{p,12}(T_{z,12}s+1)}{T_{w,12}{}^2 s^2 + 2\zeta_{12}T_{w,12}+1} \\ 0 & \dfrac{K_{p,22}}{T_{22}s+1} \end{bmatrix} \quad (1)$$

Input and output values in (1) are $\mathbf{u}(s) = \left[FiO_2(s)\ \ q_g(s)\right]^T$ and $\mathbf{y}(s) = \left[pO_2(s)\ \ pCO_2(s)\right]^T$, respectively. Note that the estimated dynamics are calculated for the oxygenator only, where the transport time-delay is neglected. Coupling from FiO_2 gas-inflow too is negligible small, since the total gas-flow is not changed by the oxygen fraction in the gas. The model estimation process was repeated over certain operating points of control operating range, with q_g = [0.5 … 5.5] l/min and q_b = [1 … 5] l/min.

Constants of the coupling term $\mathbf{G}_{p,1x2}(s)$ and $\mathbf{G}_{p,2x2}(s)$ are mainly depending on gas-flow through the oxygenator, where in the case of $\mathbf{G}_{p,2x2}(s)$ a slight variation of the process gain (not time-constant) can be observed.

The blood-gas controller was designed with the H_∞-loop shaping approach. The plant was scaled and extended with the sensitivity weight for the control error

$$\mathbf{w}_1(s) = \begin{bmatrix} \dfrac{k_{w1}(T_{w1}s+1)}{s} & 0 \\ 0 & \dfrac{k_{w2}(T_{w2}s+1)}{s} \end{bmatrix}, \quad (2)$$

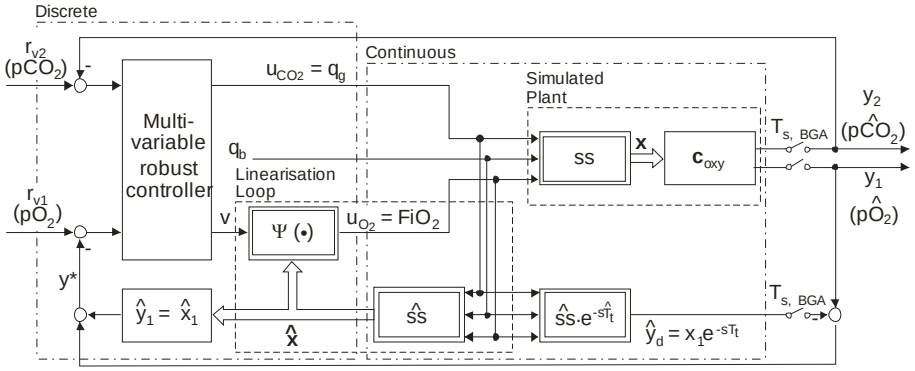

Fig 2 Multivariable blood-gas control control block diagram, with carbon dioxide control (upper part) and oxygen control (lower part). The estimated plant $\hat{s}s$ and the estimated plant including time-delay $e^{-s\hat{T}_t}$ form the Smith-Predictor, where the state vector estimation $\hat{\mathbf{x}}$ is used for the input-output linearisation of the oxygen process $\Psi(\cdot)$.

to include integral action and a relatively low pass frequency. Multiplicative input uncertainty was assumed for the blood-gas process, resulting from uncertainties in the gas-flow values (gas leaking). This input uncertainty was approximated to 20% at low frequencies. For linearisation and oxygenator (diffusion capacity) were assumed. Uncertainties were lumped at the output [5] to

$$\mathbf{I}(s) = \max_{\mathbf{G}_p(s)\in\Pi} \bar{\sigma}\left(\left[\left(\mathbf{G}_p(s) - \mathbf{G}(s)\right]\mathbf{G}^{-1}(s)\right)\right). \qquad (3)$$

The H_∞-controller was determined via the mixed-sensitivity loop-shaping control problem for robust performance, reduced to 6th-order via balanced truncation and discretised at the sampling time T_s = 6s.

Simulation results

Simlations were conducted in MATLAB/Simulink, with the full process model including time-delays and process uncertainty. A sample result is given in Fig 3, where reference steps were applied to oxygen and carbon dioxide partial pressure control. The controller shows relatively fast settling times, with an overshoot of 10% and good coupling behaviour compared to previous results [4]. The disturbance rejection of an arterial blood-flow step from 2 to 1 l/min is sufficiently good.

Discussion

A multivariable controller for blood-gas control was designed via the H_∞-loop shaping approach at a certain operating point using estimated process models of the input/output linearised plant. The controller shows good behaviour in terms of reference tracking and disturbance rejection and was tested in simulations. Controller coupling and pCO_2-transfer function terms have varying time-constant and gain depending on the control input gas-flow. This was not modelled as uncertainty in the current approach. A reasonable method would be for example a repeated controller design at certain gas-flow operating points and the implementation via a bumpless controller blending scheme. The introduction of real parametric uncertainty and a controller design with the structured singular value μ is suggested to be less conservative and to increase the control performance. These issues will be subject of future work.

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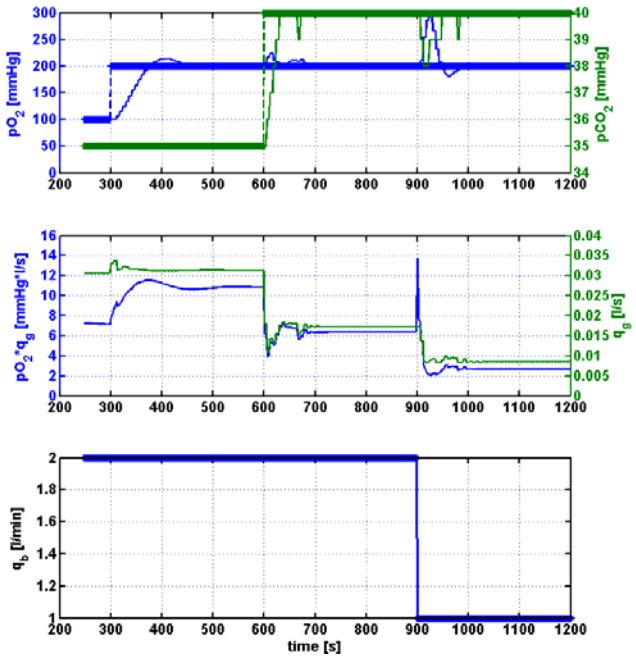

Fig 3 Response of the multivariable controller to reference changes and a change of blood flow.