A NOVEL FUZZY BASED INTERNAL MODEL CONTROLLER DESIGN OF A PERFUSION SYSTEM FOR CPB SURGERY CONDITIONS

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ABSTRACT
During cardiac surgery CardioPulmonary Bypass (CPB) takes over the function of the Heart and Lungs. A Heart Lung Machine (HLM) support maintains the Oxygen content and the circulation of blood of the patient. The HLM system is managed by perfusionist manually. The perfusionist often makes small adjustments in the system to maintain flow and pressure of Blood Gases. This maintenance process can be tedious and leads to human errors. By an introduction of an automatic controller in this system the variables can be perfectly controlled. In this work real time Blood Gas Analyzer (BGA) reports of various CPB surgery patients are collected and completely analysed and for that oxygenation process values a Fuzzy Based Internal Model Controller Designed for a Perfusion System and tested in MATLAB Simulink for different CPB Surgery conditions. So this control strategy presented ensures the patient’s safety.

Keywords: cardiopulmonary bypass (CPB), blood gas analyser (BGA), partial pressure of carbon dioxide (PCO2), partial pressure of oxygen (PO2), fraction of oxygen (FiO2).

1. INTRODUCTION
CardioPulmonary bypass (CPB) is a form of Extra Corporeal Circulation (ECC), commonly used as a routine treatment in cardiovascular surgery for artery disease, valve disease and Heart transplantations. During CPB surgery the functions of the Heart and Lungs are taken over by HLM support. HLM mechanically circulates and oxygenates the blood thereby providing the cardiothoracic surgeon a bloodless, motionless operating field. In a HLM perfusion system the blood from the patient body is continuously collected and returned through plastic tubing to allow the health care professionals to maintain an artificial organ function like Artificial Heart (Blood pump), Artificial Lungs (Oxygenator) on the blood during CPB surgery. Block diagram of Heart Lung Machine is shown in Figure1.

2. CPB SURGERY
During the CPB surgery condition the HLM machine used as an artificial lung, it has an alternative oxygenator where gas exchange takes place in a thin micro porous membrane with a high surface area. This gas exchange process is controlled by the gas fractions and flow rate of the total mixed Blood Gases injected into the oxygenator. This operation is regulated manually by a specialized technician called perfusionist. The gas exchange process of the HLM oxygenator is a complicated and nonlinear process. So an automatic controller approach can be introduced in the HLM system for the Blood Gases regulation which improves the performance of the system, and increases the patient safety by reducing the human errors.

3. BGA REPORT ANALYSIS
Various CPB surgery patients’ real time Blood Gas Analyzer reports measured during HLM support are collected. These BGA reports are completely analysed by comparing with past recovered patients records. The oxygenation process input value FiO2 (%) and output value PO2 (mmHg) simultaneously changes, which depends on patient’s age and their physical conditions. Taking the suggestions from perfusionist and specialized doctors the Oxygenation process values are separated into
four conditions Mild, Moderate, Deep and Profound depending on its temperature level. Polynomial function of the Oxygenation processes values for these four temperature condition are identified using curve fitting toolbox in MATLAB environment.

4. FUZZY BASED INTERNAL MODEL CONTROLLER

A fuzzy logic system can be considered as a nonlinear mapping of an input data vector into an output vector where this nonlinear relation is defined by linguistic expressions which are computed with numbers. Thus, a fuzzy logic system is unique in its ability to handle numerical data and linguistic information.

In this work Takagi-Sugeno (T-S) fuzzy system is chosen which is similar to the Mamdani method in many aspects. In general the fuzzy inference process, the fuzzifying inputs and the fuzzy operator application, are same. But the output membership functions of T-S type fuzzy inference is only linear or constant. The structure of fuzzy IMC developed for a perfusion process of HLM system is shown in Figure-2. It consists of an inverse Fuzzy model and the forward Fuzzy model, which is connected in parallel with the process. The controller is an inverse Fuzzy model of the process with the IMC scheme; the aim is to accurate fixing system. The difference between the process model output and the forward fuzzy model is calculated as modeling error em(k). The em(k) signal is given to the first order low pass filter \( 1 / \lambda s + 1 \) (\( \lambda \) value is fixed by 1/5 to 1/10 th of open loop time constant) and the output is subtracted from the set point (PO2 ref). Then, it is given as one of the inputs to the inverse Fuzzy model.

**Mild temperature condition**

Obtained fuzzy rules for Inverse Fuzzy model (Mild)

Model 1
\[
\text{FiO2} (k) = 1.013 \times \text{FiO2} (k-1) + 0.1996 \times \text{PO2} (k) - 0.2019 \times \text{PO2} (k-1) - 0.238
\]

Model 2
\[
\text{FiO2} (k) = 1.007 \times \text{FiO2} (k-1) + 0.07625 \times \text{PO2} (k) - 0.07722 \times \text{PO2} (k-1) - 0.2284
\]

Model 3
\[
\text{FiO2} (k) = 0.9772 \times \text{FiO2} (k-1) + 0.1642 \times \text{PO2} (k) - 0.1604 \times \text{PO2} (k-1) + 0.4876
\]

Model 4
\[
\text{FiO2} (k) = 0.9803 \times \text{FiO2} (k-1) + 0.1033 \times \text{PO2} (k) - 0.101 \times \text{PO2} (k-1) + 0.8498
\]

Obtained fuzzy rules for Forward Fuzzy model (Mild)

Model 1
\[
\text{PO2} (k) = 0.1599 \times \text{PO2} (k-2) - 0.01183 \times \text{PO2} (k-3) + 4.661 \times \text{FiO2} (k-1) - 88.1
\]

Model 2
\[
\text{PO2} (k) = 0.3771 \times \text{PO2} (k-2) - 0.01206 \times \text{PO2} (k-3) + 3.735 \times \text{FiO2} (k-1) - 74.23
\]

Model 3
\[
\text{PO2} (k) = 0.2599 \times \text{PO2} (k-2) - 0.01781 \times \text{PO2} (k-3) + 4.334 \times \text{FiO2} (k-1) - 91.57
\]
Model 4
\[ PO_2 (k) = 0.3071 \cdot PO_2 (k-2) - 0.01829 \cdot PO_2 (k-3) + 4.196 \cdot FiO_2 (k-1) - 95.18 \]

Membership diagram for Forward Fuzzy Model (Mild)

Model 3
\[ PO_2 (k) = 0.04376 \cdot PO_2 (k-2) - 0.008823 \cdot PO_2 (k-3) + 4.985 \cdot FiO_2 (k-1) - 35.08 \]

Model 4
\[ PO_2 (k) = -0.03157 \cdot PO_2 (k-2) - 0.008903 \cdot PO_2 (k-3) + 4.962 \cdot FiO_2 (k-1) - 8.961 \]

Obtained fuzzy rules for Inverse Fuzzy model (Moderate)

Model 1
\[ FiO_2 (k) = 0.9903 \cdot FiO_2 (k-1) + 0.1925 \cdot PO_2 (k) - 0.1909 \cdot PO_2 (k-1) + 0.04971 \]

Model 2
\[ FiO_2 (k) = 0.9838 \cdot FiO_2 (k-1) + 0.1908 \cdot PO_2 (k) - 0.1878 \cdot PO_2 (k-1) + 0.1318 \]

Model 3
\[ FiO_2 (k) = 0.9838 \cdot FiO_2 (k-1) + 0.1908 \cdot PO_2 (k) - 0.1878 \cdot PO_2 (k-1) + 0.1318 \]

Model 4
\[ FiO_2 (k) = 0.9885 \cdot FiO_2 (k-1) + 0.1847 \cdot PO_2 (k) - 0.1826 \cdot PO_2 (k-1) + 0.1171 \]

Obtained fuzzy rules for Forward Fuzzy model (Moderate)

Model 1
\[ PO_2 (k) = 0.008531 \cdot PO_2 (k-2) - 0.01229 \cdot PO_2 (k-3) + 4.918 \cdot FiO_2 (k-1) - 17.56 \]

Model 2
\[ PO_2 (k) = -0.0139 \cdot PO_2 (k-2) - 0.010 \cdot PO_2 (k-3) + 4.933 \cdot FiO_2 (k-1) - 11.98 \]

Obtained fuzzy rules for Forward Fuzzy model (Moderate)

Figure-4. Membership diagram for Forward fuzzy model (Mild)

Figure-5. Membership diagram for Inverse fuzzy model (Moderate)

Figure-6. Membership diagram for Forward fuzzy model (Moderate)
Deep temperature condition

Obtained fuzzy rules for Inverse Fuzzy model (Deep)

Model 1
\[ \text{FiO}_2 (k) = 1.002 \times \text{FiO}_2 (k-1) + 0.1358 \times \text{PO}_2 (k) - 0.1364 \times \text{PO}_2 (k-1) + 0.0172 \]

Model 2
\[ \text{FiO}_2 (k) = 0.9738 \times \text{FiO}_2 (k-1) + 0.1936 \times \text{PO}_2 (k) - 0.1885 \times \text{PO}_2 (k-1) + 0.0526 \]

Model 3
\[ \text{FiO}_2 (k) = 0.9916 \times \text{FiO}_2 (k-1) + 0.1889 \times \text{PO}_2 (k) - 0.1873 \times \text{PO}_2 (k-1) + 0.0351 \]

Model 4
\[ \text{FiO}_2 (k) = 0.9921 \times \text{FiO}_2 (k-1) + 0.2006 \times \text{PO}_2 (k) - 0.199 \times \text{PO}_2 (k-1) - 0.0174 \]

Obtained fuzzy rules for Forward Fuzzy model (Deep)

Model 1
\[ \text{PO}_2 (k) = 0.06668 \times \text{PO}_2 (k-2) - 0.005634 \times \text{PO}_2 (k-3) + 4.819 \times \text{FiO}_2 (k-1) - 7.286 \]

Model 2
\[ \text{PO}_2 (k) = 0.03141 \times \text{PO}_2 (k-2) - 0.00899 \times \text{PO}_2 (k-3) + 4.932 \times \text{FiO}_2 (k-1) - 2.756 \]

Model 3
\[ \text{PO}_2 (k) = -0.003548 \times \text{PO}_2 (k-2) - 0.005018 \times \text{PO}_2 (k-3) + 4.975 \times \text{FiO}_2 (k-1) - 5.944 \]

Model 4
\[ \text{PO}_2 (k) = 0.0661 \times \text{PO}_2 (k-2) - 0.005649 \times \text{PO}_2 (k-3) + 4.822 \times \text{FiO}_2 (k-1) - 7.288 \]

Figure-7. Membership diagram for Inverse fuzzy model (Deep)

Profound temperature condition

Obtained fuzzy rules for Inverse Fuzzy model (Profound)

Model 1
\[ \text{FiO}_2 (k) = 0.9952 \times \text{FiO}_2 (k-1) + 0.1461 \times \text{PO}_2 (k) - 0.1456 \times \text{PO}_2 (k-1) + 0.0663 \]

Model 2
\[ \text{FiO}_2 (k) = 0.9793 \times \text{FiO}_2 (k-1) + 0.1936 \times \text{PO}_2 (k) - 0.1896 \times \text{PO}_2 (k-1) - 0.3472 \]

Model 3
\[ \text{FiO}_2 (k) = 0.9853 \times \text{FiO}_2 (k-1) + 0.207 \times \text{PO}_2 (k) - 0.2039 \times \text{PO}_2 (k-1) - 0.324 \]

Obtained fuzzy rules for Forward Fuzzy model (Profound)

Model 1
\[ \text{PO}_2 (k) = -0.03498 \times \text{PO}_2 (k-2) + 0.04162 \times \text{PO}_2 (k-3) + 4.58 \times \text{FiO}_2 (k-1) + 117.9 \]

Model 2
\[ \text{PO}_2 (k) = 0.1212 \times \text{PO}_2 (k-2) - 0.008372 \times \text{PO}_2 (k-3) + 4.489 \times \text{FiO}_2 (k-1) + 79.74 \]

Figure-8. Membership diagram for fuzzy forward model (Deep).
Model 3
PO2 (k) = 0.05218 * PO2 (k–2) -0.01035 * PO2 (k–3) + 4.694 * FiO2 (k–1) + 97.6

Membership diagram for Inverse Fuzzy Model (Profound)

Figure-9. Membership diagram for Inverse fuzzy model (Profound)

Membership diagram for Forward Fuzzy Model (Profound)

Figure-10. Membership diagram for Forward fuzzy model (Profound)

5. SIMULATION RESULTS

Mild temperature condition

Figure-11. Perfusion system output (Mild temperature).

FiO2 controller output (Mild temperature).

Moderate temperature condition

Figure-13. Perfusion system output (Moderate temperature).
DISCUSSIONS

Various CPB surgery patients real time Blood Gas Analyzer reports measured during HLM support are collected. These BGA reports are completely analyzed by comparing with past recovered patients records. The oxygenation process input value FiO₂ (%) and output value PO₂ (mmHg) is only considered. Taking the suggestions from perfusionist and specialized doctors the Oxygenation process values are separated into four conditions Mild, Moderate, Deep and Profound depending on its temperature level. Polynomial function of the Oxygenation processes values for these four temperature condition are identified using curve fitting toolbox in MATLAB Environment. A Fuzzy Based Internal Model Controller is developed for this CPB Surgery Conditions. The performance of the controller for the four CPB surgery condition is tabulated.

Figure-14. FiO₂ controller output (Moderate temperature).

Figure-15. Perfusion system output (Deep temperature).

Figure-16. FiO₂ controller output (Deep temperature).

Figure-17. Perfusion system output (Profound temperature).

Figure-18. FiO₂ controller output (Profound temperature).
Table-1. Fuzzy based internal model controller performance for the four CPB surgery conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mild</th>
<th>Moderate</th>
<th>Deep</th>
<th>Profound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range</td>
<td>37 °C to 32 °C</td>
<td>32 °C to 28 °C</td>
<td>28 °C to 18 °C</td>
<td>Below 18 °C</td>
</tr>
<tr>
<td>Setpoint PO2</td>
<td>250</td>
<td>300</td>
<td>325</td>
<td>425</td>
</tr>
<tr>
<td>Controller output FiO2</td>
<td>64.048</td>
<td>64.662</td>
<td>64.908</td>
<td>66.285</td>
</tr>
<tr>
<td>Perfusion system output PO2</td>
<td>249.88</td>
<td>299.94</td>
<td>325.05</td>
<td>425.72</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Fuzzy Based Internal Model Controller is developed for CPB Surgery Condition is tested in Matlab Simulink environment shows a better performance. The controller is an inverse Fuzzy model of the process with the IMC scheme. The main Objective of this process to have an accurate fixing system, so by feeding back the modeling error signal to the inverse controller makes the Perfusion system immune to load or any electrical fault disturbances. In future studies this Fuzzy Based Internal Model Controller can be implemented for perfusion system of the Heart Lung machine to have a complete automated control during CPB surgery conditions.

REFERENCES


