Evaluation of Control Schemes for Blood Pressure Regulation

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Abstract: Cardiovascular system plays an important role in human as well as other living beings for maintaining the blood flow throughout the body. During cardiac surgery, there will be variations in Mean Arterial Pressure (MAP) which leads to various complications during postsurgical treatment. In order to keep the MAP at desired level, vasodilator and vasoconstrictor drugs are used. The drug dosage is to be controlled at the accurate rate to attain the desired level of MAP. The adjustment of drug infusion rate is usually done manually by the anaesthesiologist during surgeries and for ICCU patients. The manual control mechanisms results are time consuming and less accurate. So an Automatic Drug Delivery System (ADDS) has to be implemented for the control of drug infusion rate which in turn controls the MAP and ensures patient’s safety during surgery. In this paper, various control schemes for the control of MAP are discussed and their performances are compared.

Key words: Control schemes • Drug dosage • Mean arterial pressure (MAP) • Safety • Surgery

INTRODUCTION

In humans, the cardiovascular system is responsible for maintaining the blood flow throughout the body. The function of cardiovascular system is the transportation of nutrients and oxygen to the tissues and removal of waste products. To achieve this, the pressure level at different blood vessels and tissues should be properly maintained. The physiological process for regulation of Mean Arterial Pressure (MAP) involves several feedback paths and nonlinear interactions which makes the system complex. The fluctuations in blood pressure during surgeries results in bleeding, heart cell damage, bursting of vessels, disruption of suture lines etc. [1, 2]. To regulate the MAP (either increase or decrease), which reduces the complications during surgeries and in Intensive Critical Care Unit (ICCU) various vasodilator and vasoconstrictor drugs are used. The commonly used drugs are Sodium Nitroprusside (SNP), Noradrenaline (NAR), Halotheane, Hexamethonium, Pentolinium, Trimethaphan and Nitroglycerin [1]. Among these, SNP and Nitroglycerin are widely used drugs during cardiac surgeries [3]. When these drugs are infused intravenously, it causes peripheral vasodilation on smooth muscles. Clinically, this intravenous infusion is done by manual method. The manual methods are time consuming and of poor quality, an Automatic Drug Delivery System (ADDS) is to be modeled and controlled to regulate the MAP at desired limits. While modeling the controller, the patient’s sensitivity to drug and the disturbances that contribute to the changing conditions of patients are to be considered [3].

Modeling of Patient Response: The most widely used drug is SNP since it has minimum side effects and higher vasospasm [1]. Increase in the amount of SNP leads to formation of cyanide due to metabolism activities which is toxic to humans and decrease in the amount of SNP leads to lowering of MAP which causes diminished blood flow or circulatory collapse [4]. Hence the desired limit of the SNP has to be maintained to regulate the MAP. For this reason, two restraints are to be taken into account: (i) Maximum allowable infusion rate and (ii) Incremental increase in the infusion rate should be limited [3]. The patient model is represented using a first-order transfer
function with a transportation delay and two time delays modeled [6] using correlation analysis with pseudo-random binary signal [5]. The dynamic model of patient MAP to SNP infusion rate is given as [2],

\[
MAP = MAP_0 + \Delta MAP + MAP_n
\]  

(1)

where MAP is mean arterial pressure, MAP_0 is initial blood pressure \(\Delta MAP\) is the change in blood pressure due to infusion and MAP_n is noise. The patient model is the transfer function between the change in blood pressure and SNP infusion rate represented as;

\[
\frac{\Delta MAP}{SNP} = \frac{Ke^{-T_i (1 + \alpha e^{T_s})}}{(1 + T_s^{2})}
\]

(2)

where \(K\) is drug sensitivity (mmHg/mL/h), \(T_i\) is initial transport delay, \(T_s\) is recirculation time delay, \(\alpha\) is recirculation constant and \(\theta\) is time constant.

Types of Control Schemes: An ADDS requires an controller to control the MAP to desired limits by controlling the drug infusion rate simultaneously. The various types of control mechanisms implemented are as follows.

- Conventional PI/PID Controller
- Constrained PI/PID Controller
- Adaptive PI Controller
- Internal Model Controller (IMC)
- Model Predictive Controller (MPC)
- Model Reference Adaptive Controller (MRAC)
- Artificial Neural Networks (ANN)
- Fuzzy Logic Controller (FLC)

**Conventional PI/PID Controller:** Most widely used controller in the field of process control because of its simplicity and robustness is the three term controller called as Proportional-Integral-Derivative Controller (PID). The common tuning method for closed loop response of PID controller is Zeigler-Nichols method. Zeigler-Nichols tuning method is applied to obtain the \(K_p\), \(\tau_i\) and \(\tau_d\) values of the closed loop transfer function of the converter [7]. The proportional gain is slowly increased by giving small periodic disturbance to the process. At one point of time, closed loop response tends to produce sustained oscillations and Table 1 shows the tuning parameters. From the oscillations obtained, the ultimate gain \(K_u\) and the period of oscillation known as ultimate period \(P_u\) are calculated. Figure 1 shows the closed loop block diagram of PID controller.

Table 1: Tuning Parameters
<table>
<thead>
<tr>
<th>CONTROLLER</th>
<th>(K_p)</th>
<th>(\tau_i)</th>
<th>(\tau_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>(K_p/2)</td>
<td>(P_u/1.2)</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>(K_p/1.7)</td>
<td>(P_u/2)</td>
<td>(P_u/8)</td>
</tr>
</tbody>
</table>

**Constrained PI/PID Controller:** In this controller, the tuning method and determination of the controller parameters are similar to that of Conventional PI/PID controller. But here two constraints are taken into account as discussed in modeling of patient response. The first constraint is the maximum allowable infusion rate of the drug. The increase in the amount of SNP drug becomes toxic due to metabolism activities inside the body. This value is determined using the function:

\[
U_M = W_p/M \cdot C_s^{-1}
\]

(3)

where \(W_p\) is the patient’s weight (kg), \(C_s\) is the drug concentration (mg/mL), \(i_0\) is the maximum recommended dose (mg/kg hr). The second constraint is the incremental increase in the infusion rate. If the drug infused increases the desired amount then the MAP will be lowered which causes many complications. In this case, the maximum incremental change in drug infusion rate is limited to 20% of the allowable infusion rate of the drug [3, 4]. Figure 2 shows the closed loop block diagram of Constrained PI/PID controller.

**Adaptive PI Controller:** Adaptive PI controller has the ability for disturbance rejection. This controller will be able to deal the disturbances caused by the cardiovascular system such as sudden increase or decrease in MAP. The control mechanism will be able to render disturbance that are fatal or non-fatal [8]. The parameters of adaptive PI controller are determined using Zeigler-Nichols tuning method. The parameters of the controller will be able to adapt to dynamic changes that occurs in the patient and disturbance model. The Adaptive PI Controller is given by [9]:

\[
PI = K_p(1 + \frac{1}{T_i S})
\]

(4)

where \(K_p\) is the controller gain and \(T_i\) is the integral time.

**Internal Model Controller (IMC):** The IMC structure generally consists of three blocks such as controller, internal model and internal model loop. The IMC principle is that the control can be achieved only if the control system encapsulates, either implicitly or explicitly, certain representation of the process to be controlled.
The controller block uses the error signal to compute the values of the process output. The internal model block is the reference model to that of the process which is to predict the process output. The internal model loop is used to provide the difference between the process output and internal model output which is referred as error. The perfect control scheme can be obtained only if the exact model of the process is used [1, 5, 7]. Figure 3 shows the closed loop block diagram of IMC.

**Model Predictive Controller (MPC):** Model Predictive Controller is the process control technology which uses the concept of process model and open loop optimal feedback. The process model is used to predict the values of the process output. The model output is compared with the process output which produces the residues. This residue is given as the input to the controller to control the drug infusion rate. At every sampling time, past outputs and inputs are used to estimate the current state.
of the system. The optimization technique is used to determine the optimal open loop policy from the estimated state. The controller consists of two operations such as estimation and optimization [10, 11]. Figure 4 shows the closed loop block diagram of MPC.

**Model Reference Adaptive Controller (MRAC):** The transfer function parameter of the patient model may vary differently for each patient. So, an adaptation mechanism has to be implemented for the feedback system in controlling the drug infusion rate to obtain the desired MAP. The control scheme used for regulating the blood pressure consists of design of reference model which should be the best match to that of the process. This control mechanism can be achieved by formulating the set of process equations and reference model equations which represents the desired response characteristics [12, 13]. MRAC are most widely used for multi-drug infusion rate control [14, 15]. The process equations and model equations represented by 12 are given as:

\[
\dot{x}_p(t) = A_p x_p(t) + B_p u_p(t)
\]

\[
y_p(t) = C_p x_p(t)
\]

where \(x_p(t)\) is the \((n \times 1)\) process state vector, \(u_p(t)\) is the \((m \times 1)\) control vector, \(y_p(t)\) is the \((m \times 1)\) process output vector and \(A_p, B_p, C_p\) are matrices with appropriate dimensions.

\[
\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t)
\]

\[
y_m(t) = C_m x_m(t)
\]

where \(x_m(t)\) is the \((n \times 1)\) model state vector, \(u_m(t)\) is the \((m \times 1)\) control vector, \(y_m(t)\) is the \((m \times 1)\) model output vector and \(A_m, B_m, C_m\) are matrices with appropriate dimensions. Figure 5 shows the closed loop block diagram of MRAC.

**Artificial Neural Networks (ANN):** ANN is mainly used in biomedical systems for managing the hemodynamic variables of the patients. The application of neural network to control the drug infusion rate is slightly efficient to that of other controllers [16]. A neural network with nonlinear elements offers distinct advantages over conventional controllers to achieve desired performance. The multi-layer ANN (MNN) consists of three layers- the input layer, hidden layer and output layer. The nonlinear processing elements at the hidden and output layers multiply the incoming signals with weights and generate output signals according to sigmoid function with a bias [17] as shown in Figure 6.

**Fuzzy Logic Controller (FLC):** Fuzzy Logic Controller has found many successful industrial applications and demonstrated significant performance improvements [18]. The fuzzy controller has the advantage of changing its structure flexibly by using different rule base and commands from the expert system unit. The analytical design of the fuzzy process is less when compared to that of linear control systems. The design of FLC consists of three units- fuzzification, fuzzy expert system and defuzzification as shown in Figure 7. The difference between the MAP and desired MAP is taken as the error [19]. This error signal is used as one of the input to the fuzzification unit. Another input is the rate of change of error. The fuzzy expert system consists of rule base based on the controller works.

![Fig. 5: Block Diagram of MRAC](image.png)
Constrained PI Controller & 210 & 250 & 50.96 & 600 \\
2. Constrained PID Controller & 110 & 180 & 40.32 & 400 \\
3. Adaptive PI Controller & 190 & 0 & 0 & 200 \\
4. IMC & 150 & 0 & 0 & 742 \\
5. MPC & 195 & 250 & 38.55 & 4000 \\
6. MRAC & 210 & 0 & 0 & 1232 \\
7. ANN & 300 & 0 & 0 & 960 \\
8. FLC & 230 & 260 & 39.02 & 800 \\

Comparison Results: The control strategies used for the control of blood pressure regulation mainly focuses on the control of drug infusion rate. The controlled drug infusion to obtain the desired MAP limits is discussed in the above sections. The performance of each control mechanisms are compared using the time domain specifications as shown in Table 2. Furthermore, the performance can be improved using optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Bee Colony Algorithm, Cuckoo Optimization Algorithm and Firefly Algorithm.

CONCLUSION

Mean Arterial Pressure (MAP) can be brought to the desired MAP by controlling the infusion of vasodilator and vasoconstrictor drugs. The sensitivity, transport lag and time delay may vary for different patients when the drug is infused intravenously. The effects of these variations are solved by using various convectional as well as advanced controllers and soft computing techniques. Thus the performance of these controllers are reviewed and discussed in this paper.
REFERENCES


