A Computerized Drug Delivery Control System for Regulation of Blood Pressure

K. Y. Zhu*1, H. Zheng1 and D. G. Zhang1
1School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798

Received 1 January 2007; revised 2 February 2007, accepted 3 March 2007

Abstract
Many patients presenting hypertension before/after surgery should need to receive adequate medication. For example, patients with dissecting aneurysm often show extreme hypertension and an adequate control of blood pressure of the patient will lead to good surgical outcome. On the other hand, untreated hypertension after surgery may create complication. Therefore, hypertension control after/before surgery is important. In this paper, postsurgical hypertension control for cardiac patients, without loss of generality, will be focused. From the past experience, elevated blood pressure often occurs in the early hours following open-heart surgery. Basically, there are several medications such as Sodium Nitroprusside (SNP) and Nitroglycerin, etc., which are commonly used for the treatment of postsurgical hypertension of the cardiac patient. We consider here Sodium Nitroprusside in the design of the control system. However, due to a wide range of patients’ drug sensitivities to SNP, manual control by clinical personnel could be very tedious, time consuming and inconsistent. An automatic drug delivery controller based on feedback method may quickly reduce the oscillatory change in mean blood pressure through infusion of SNP. In this paper, an adaptive Proportional-Integral (PI) control of mean blood pressure using SNP is presented. A new algorithm updating variations in time delay and sensitivity of the system is proposed and its effectiveness in the treatment of the hypertension patient is discussed. For demonstration, simulations under clinical conditions are carried out.

Keywords
Adaptive control, mean arterial blood pressure, PID controller, time-varying systems

1. INTRODUCTION
It is known that hypertension may occur to many patients before/after surgery. An adequate control of blood pressure through medication will lead to good surgical outcome and can reduce complication. Therefore, perioperative control of blood pressure would be important in clinical practice. Although hypertension control before surgery is necessary and helpful, in this paper postsurgical hypertension control of cardiac patients will be considered. However, the control strategy presented in this paper might also be applicable to other hypertension cases.

Postsurgical hypertension for cardiac patients is quite common. This is particularly evident after coronary artery bypass grafting procedures. Untreated hypertension after a cardiac operation may result in increased bleeding, disruption of suture lines etc. To decrease the chances of complication, it is necessary to reduce the elevated blood pressure as soon as possible. Continuous infusion of vasodilator drugs, such as sodium nitroprusside (SNP) or Nitroglycerin can quickly lower the blood pressure in most patients. Different drugs may result in different time of regulation and has different sensitivity. Therefore, in this case different models are needed for describing the dynamic behaviors. Here treatment of hypertension using SNP for cardiac patients will be considered. Compared to the manual control of hypertension, the advantage of automation by application of feedback control techniques would be evident. However, due to a wide range of patient’s sensitivities to the drug, and the variation of the reaction time of the drug, a conventional control technique could not provide satisfactory control of hypertension. Previously, the primary emphasis in the design of SNP blood pressure controllers was to achieve a settling time of less than 10 min, and a maximum overshoot of less than 10 mm Hg, as specified by Slate in [1]. The following work and modification of the original Proportional-Integral-Derivative (PID) controller by Slate, and Sheppar in [2] have led to the postulation of the well-known mean arterial pressure (MAP) model responding to SNP infusion and routine clinical practice of such a controller on postoperative patients. Many evaluations on different controllers

* K. Y. Zhu: School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, email:ekyzhu@ntu.edu.sg
have also been presented. Multiple-model based control systems have been proposed by He, et al. [3], Martin et al. [4], Yu et al. [5] and Palerm et al. [6] to handle variations in the drug sensitivity, where several mathematical models are used and identified on-line. A controller based on one-step ahead prediction is designed by Behbehani and Cross [7], however, it is tested with the fixed system parameters. A self-tuning regulator for control of mean arterial blood pressure is presented by Delapasse et al. [8], where variations in time delay are accommodated through on-line estimation. An adaptive neural network control system and model-based predictive controllers (here, a mathematical model is used) have also been proposed respectively by Polycarpou and Conway [9], Kwok et al. [10] and Meng et al. [11], however, they lack the simple structure and usually need complicated computations. A model reference adaptive control system is presented by Pajunen et al. [12], in which a reference mathematical model is introduced so that the system output follows the reference model.

In this paper, an adaptive proportional-integral (PI) tuning for blood pressure control of hypertension patients is proposed. A new tuning method updating changes in patient’s sensitivity, and variations in the reaction time is proposed. The main difference of the method compared to the previous ones is that the sensitivity and time delay can be directly estimated using the algorithms presented in this paper. They are based on the parameters identified, have simple forms and therefore can be computed easily. Simulation results show that it is effective and can provide satisfactory control performance. A further clinical trial will be carried out in a near future. This paper is organized as follows. In Section 2, a mathematical description of blood pressure of hypertension patients is presented and some concerned problems are also addressed. In Section 3, an adaptive PI controller for blood pressure control is presented and its effectiveness is investigated. Simulations for demonstration of the control system are carried out in Section 4. In Section 5, implementation for real testing is presented and finally, discussion and conclusion are given in Section 6.

2. PROBLEM FORMULATION
A dynamic model of the mean arterial pressure (MAP) of patients under influence of SNP was developed by Slate in [1] and is given by

\[ MAP = P_0 - P_\Delta + P_d + n \]  

where \( MAP \) is the mean arterial pressure, \( P_0 \) is the initial mean blood pressure, also called the background pressure, \( P_\Delta \) is the change in the mean blood pressure due to infusion of SNP, \( P_d \) is the change in the mean pressure due to the renin reflex action which is the body’s reaction to the use of a vasodilator drug, \( n \) is a random noise. In this paper, it is assumed that \( P_0 \) is a constant.

A continuous-time model describing the relationship between the change in blood pressure and the SNP infusion rate is given by

\[ P_\Delta(s) = \frac{K e^{-T_i s} (1 + \alpha e^{-T_2 s})}{1 + \tau s} I(s) \]  

where \( P_\Delta(s) \) is the change in the mean blood pressure, \( I(s) \) is the infusion rate, \( K \) with \( 0.25 \leq K \leq 8 \) is the sensitivity representing the patient’s sensitivity to drug, \( \alpha \) with \( 0 \leq \alpha \leq 0.1 \) is the recirculation constant reflecting the effect of recirculated drug to patient’s blood pressure. \( T_i \) with \( 20 \text{ sec} \leq T_i \leq 60 \text{ sec} \) (here, \( e \) represents exponential function) is the initial transport delay (or time delay) from the injection site. Here, the injection site is the infusion pump. \( T_2 \) with \( 20 \text{ sec} \leq T_2 \leq 60 \text{ sec} \) is the recirculation time delay which corresponds to the time required for the drug to flow through patient’s body. \( \tau \) with \( 40 \text{ sec} \leq \tau \leq 60 \text{ sec} \) is the system time constant (the above values of the system parameters are given by Slate in [1]). It is shown that this model is a good approximation of the observed background activity and is achieved through experiments. However, due to neglecting the interactions of arterial pressure with other state variables, such as cardiac output, this single-input and single-output model may not be valid for large changes of the infusion rate. In this case, the system should be analyzed by using the piece-wise linearity. In this paper, we focus on adaptive PI tuning problem and the large change in the infusion rate is constrained as it may cause toxic side effects. Hence, the model given in (2) should be valid and be used in the design.

Discretizing the continuous-time model given in (2) with the sampling time of 15 sec. yields the following discrete-time model

\[ P_\Delta(t) = \frac{q^{-d} (b_0 + b_1 q^{-d})}{1 - a q^{-1}} I(t) \quad ; \quad b_0 \geq 0 \]  

where \( a \) and \( b_1 \) are the discrete time parameters.
where $q^{-1}$ denotes a unit delay operator, 

$$a = e^{-r}, \quad b_0^i \text{ and } b_1^i \text{ are the parameters of the numerator, } d_1 \text{ and } d_2 \text{ are the time delays obtained from sampling the continuous-time model. Due to variations of each patient's sensitivity and reaction time to the infusion rate, these parameters are also not constant. The parameters of the model (3) are given by Pajunen et al. in [12]. Actually, it is obtained through discretization of the continuous-time model (2). Table 1 lists the parameters of the discrete-time model.}

In this paper, the sensitivity can be classified into 3 levels: low, normal and high. If the patient's sensitivity is low, then it needs relatively higher infusion rates. For patient with higher sensitivity, relatively a lower infusion rate is required to decrease his mean blood pressure. Note that $a$ depends on the time constant, $b_0^i$ depends on the sensitivity and $b_1^i$ is determined by the sensitivity and the circulation constant.

3. ADAPTIVE PI CONTROL OF MAP

Proportional-integral and derivative (PID) controllers have been widely used owing to their simplicity and robustness shown in applications. Moreover, the tuning of the PID controller is well studied and many tuning formulae are presented. For example, a self-tuning PID control based on a frequency response method is proposed by Ho et al. [13] and it is shown that satisfactory control performance can be provided, however, it is for the plant with the fixed parameters. Another PID tuning method presented by Wang et al. [14] needs to perform a step response test to obtain the transient response of the system. In general, if the system to be controlled is of time-varying, i.e. the parameters of the system is variable with time, an adaptive tuning might be necessary to achieve satisfactory control performance and system stability, especially for those with unknown and/or variable time delays (Refer to Kurz and Goedecke [15], Keyser and Van Cauwenbergh [16], Zhu [17], and Huzmezan [18]).

If the time delay of a system is unknown but fixed, then an off-line estimation (which implies that estimation can be done before designing a controller) would be effective in the design of the control system, otherwise, an on-line estimation (which implies that a real-time estimation is done. In another words, estimation is done during injection) for updating the control system seems necessary, especially for those systems with significant dynamic variations. In [15], an explicit estimation of time delay based on the impulse responses and recursive least squares method is proposed. It is shown that this method is robust for the generalized system model, however, it needs to compute a set of errors equations and perform comparisons. A similar method is also given by Keyser and Van Cauwenbergh in [16], but here a random response of the system should be performed and a relative error calculation is carried out to determine the value of time delay. Model-based predictive control systems based on the minimization of quadratic cost functions are presented by Zhu [17] and Huzmezan [18]. It is shown that this design method can handle the system with variable time delays and the main advantage of this approach is that time delay is estimated implicitly by using the numerator of the system with an excessive number of parameters. The similar strategy is also adopted in most pole placement control systems such as by Zhu in [17].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0^i$</td>
<td>0.053</td>
<td>3.546</td>
<td>0.187</td>
</tr>
<tr>
<td>$b_1^i$</td>
<td>0.01</td>
<td>1.418</td>
<td>0.075</td>
</tr>
<tr>
<td>$a$</td>
<td>0.606</td>
<td>0.779</td>
<td>0.741</td>
</tr>
<tr>
<td>$d_1$</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>$d_2$</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1. Range of values for parameters of the discrete-time model
Since a wide range of patient’s sensitivities and time delay to SNP occurs, regulation of blood pressure would be a challenging problem and has received many researchers and engineers’ attention.

It is presented by He et al. in [3], Martin et al. in [4], Roy et al. in [5] and Palerm et al. in [6] that the multiple model control systems are able to handle variations of the system dynamics. In this approach, a finite number of models are used, each predicting the response of the subject. For each model, a controller is designed a priori so as to meet the closed-loop specifications. At each control interval, computations are performed for all controllers and actual control action to the patient is selected based on optimal criteria. An adaptive compensator is developed by Delapasse et al. in [8] for updating changes in the system dynamics. In this design, the transfer function of the system has the numerator with an excessive number of parameters so that any time delay variations from the minimum to maximum can be covered. Then, it is further approximated with a pure time delay plus a constant through an algebraic summation.

In this paper, a new algorithm updating variations of time delay and sensitivity of the system is proposed which allows us to tune PI controllers easily and realize adaptive regulation of patient’s blood pressure. Compared to the previous ones, this method provides a direct estimate of the sensitivity, and time delay using the algorithms presented in this paper. To describe in detail the method, we first introduce a PI controller as follows

\[
P_I(t) = \frac{q^{-2}(b_0 + b_1q^{-1} + b_2q^{-2} + b_3q^{-3})}{1-aq^{-1}} I(t)
\]

(6)

where \( b_i \) for \( i = 0, 1, 2, 3 \) represents the coefficients of the numerator, \( a \) represents the time coefficient of the denominator of the transfer function.

If compared with (3), a numerator with two extra parameters is used in (6). This is to cover the variation of time delay (reaction time) and a recursive least squares (RLS) algorithm for estimation is associated.

In practice, the circulation constant \( \alpha \) in equation (2) is a small number, i.e. \( \alpha \ll 1 \) (see reference [1]), which is also reflected from equation (3) where \( b_0 \ll b_1 \). Hence, by Z-transform we obtain from (2)

\[
P_\alpha(t) = \frac{q^{-d_1}K \left[ (1-e^{-\frac{mT}{\tau}}) + (e^{-\frac{mT}{\tau}} - e^{-\frac{T}{\tau}})q^{-1} \right]}{1-e^{-\frac{T}{\tau}}q^{-1}} I(t)
\]

(7)

which is the discrete-time model by ignoring the circulation constant \( \alpha \). Here, \( d_1 \) is an integer representing the minimum time delay in the discrete-time model.

By imposing

\[
q^{-d_1}K \left[ (1-e^{-\frac{mT}{\tau}}) + (e^{-\frac{mT}{\tau}} - e^{-\frac{T}{\tau}})q^{-1} \right] = q^{-2}(b_0 + b_1q^{-1} + b_2q^{-2} + b_3q^{-3})
\]

where \( m \in \{1, 0\} \), we have the following results describing the evolution of the parameters \( b_i \) for \( i = 0, 1, 2, 3 \) due to the changes in time delay \( T_1 \).

a) \( b_0 = K \left( 1-e^{-\frac{mT}{\tau}} \right) \),

\( b_1 = K \left( e^{-\frac{mT}{\tau}} - e^{-\frac{T}{\tau}} \right) \) and \( b_2 = b_3 = 0 \),

for \( T_1 \in \{T, 2T\} \),

b) \( b_1 = K \left( 1-e^{-\frac{mT}{\tau}} \right) \), \( b_2 = K \left( e^{-\frac{mT}{\tau}} - e^{-\frac{T}{\tau}} \right) \)

and \( b_0 = b_3 = 0 \), for \( T_1 \in \{2T, 3T\} \),
c) \[ b_2 = K \left( 1 - e^{-\frac{mT}{\tau}} \right), \]
\[ b_3 = K \left( e^{-\frac{mT}{2\tau}} - e^{-\frac{T}{\tau}} \right) \] and \[ b_0 = b_1 = 0, \] for \[ T_i \in \{3T, 4T\}. \]

Figure 1 shows the evolution of \( b_i \) with respect to \( T_1 \). Note that the variation of time delay causes the coefficients of \( b_i \) for \( i = 0, 1, 2, 3 \) evolves.

Through the examination above, we propose here an algorithm used to directly estimate time delay from the system parameters. That is

\[
\hat{T}_1 = \left( 1 + \frac{b_1 + 2b_2 + 3b_3}{b_0 + b_1 + b_2 + b_3} \right) T \quad (9)
\]

where \( \hat{T}_1 \) represents an estimate of \( T_1 \). In the next, we will verify its validity. A detailed verification of (9) is given. Suppose that the value of time delay is

\[
T_i \in \{T, 2T\}, \text{ then has } b_0 = K \left( 1 - e^{-\frac{mT}{\tau}} \right), \\
T_i \in \{3T, 4T\}, \text{ then has } b_0 = K \left( e^{-\frac{mT}{2\tau}} - e^{-\frac{T}{\tau}} \right), \text{ and } b_2 = b_3 = 0. \] Hence,

\[
\hat{T}_1 = T + \frac{e^{-\frac{mT}{\tau}} - e^{-\frac{T}{\tau}}}{1 - e^{-\frac{T}{\tau}}} T \approx T + \frac{1-mT-T}{1-e^{-\frac{T}{\tau}}} T = (2-m)T 
\]

(10)

In (10), the exponential function is expanded and only the first two terms in the expansion are taken. Since \( m \in \{1, 0\} \), an accurate \( T_1 \) can be obtained. If \( T_1 \in \{2T, 3T\} \), it has

\[
b_1 = K \left( 1 - e^{-\frac{mT}{\tau}} \right), \\
b_2 = K \left( e^{-\frac{mT}{2\tau}} - e^{-\frac{T}{\tau}} \right), \text{ and } b_0 = b_3 = 0. \] Hence,

\[
\hat{T}_1 = T + \frac{e^{-\frac{mT}{2\tau}} - e^{-\frac{T}{\tau}}}{1 - e^{-\frac{T}{\tau}}} T \approx T + \frac{1-mT-T}{1-e^{-\frac{T}{\tau}}} T = (2-m)T 
\]

(10)

Figure 1. Evolution of parameters in numerator \( b_i \) with respect to ratio of time delay to sampling time \( T_1 / T \).
\[ \hat{t}_i = T + \left(1 - e^{-\frac{T}{\tau}} + 2 \left( e^{-\frac{T}{\tau}} - e^{-\frac{3T}{\tau}} \right) \right) T = 2T + \frac{m T + 2 \left( -m \frac{T}{\tau} + \frac{T}{\tau} \right) T = (3-m)T}{1 - e^{-\frac{T}{\tau}}} \]

(11)

Similarly, it can also be verified that for \( T_1 \in \{3T, 4T\} \), it leads to

\[ \hat{T}_i \approx (4 - m)T \]

(12)

This has completed the verification.

To evaluate accuracy of the algorithm presented in (9), we define an error equation as follows

\[ \Delta T_i = \frac{T_i - \hat{T}_i}{T} \]

(13)

Using (9) to (12), we can easily have

\[ \Delta T = \frac{1 - e^{-\frac{T}{\tau}} - m \left( 1 - e^{-\frac{T}{\tau}} \right) \frac{T}{\tau}}{(1 - e^{-\frac{T}{\tau}})} \]

(14)

Note that it depends on \( m \) and the ratio of \( T / \tau \) and it has \( \Delta T_i = 0 \), for \( m=0 \), and \( m=1 \). Since the sampling time \( T = 15s \) is chosen and the time constant \( \tau \) varies from 40 sec. to 60 sec., we can calculate the error \( \Delta T_i \) for \( 15 / 60 \leq T / \tau \leq 15 / 40 \). Figure 2 shows \( \Delta T_i \) when both \( m \) and \( T / \tau \) vary. It is found that \( \max \{ \Delta T_i \} \leq 0.046 \) and the maximum \( \Delta T_i \) for any \( T / \tau \) occurs at \( m \approx 0.5 \).

Figure 3 represents an example of this estimation when increasing \( T_1 \), where \( T = 15 \) sec., \( \tau = 40 \) sec. are chosen. This result shows that an accurate estimate of time delay can be achieved using the proposed algorithm.

The sensitivity \( K \), and time constant \( \tau \), used in the PI controller tuning are computed by

\[ \hat{K} = \frac{b_0 + b_1 + b_2 + b_3}{1 - a} \]

(15)

---

Figure 2. The error of time delay \( \Delta T_i \) with respect to the fraction \( m \) and ratio of sampling time to time constant \( T/\tau \).
\[ \hat{\tau} = -\frac{T}{\ln |a|} \]  

(16)

where \( \hat{K} \) is the estimate of the sensitivity, while \( \hat{\tau} \) is the estimate of the time constant. Note that in (15) the coefficients \( b_i \), for \( i=0, 1, 2, 3 \), and \( a \) are used to determine \( \hat{K} \). It can be verified using (6) and (7). In (16), it is based on the sampling time and \( a \). Its verification is similar to for (16).

4. SIMULATION

The objective of the simulation is to demonstrate the effectiveness of the on-line tuning of the PI controller under the actual operating environment. All of the simulation results presented here are assumed that the initial mean blood pressure is 150 mmHg and the objective is to reduce it to 100 mmHg. The system is also corrupted by white or colored noise to reflect the real situation. The highest noise level had a variance of 4 mmHg². All the simulations are completed in the following steps: at the first step, an initial estimation of the system parameters using a recursive least squares (RLS) algorithm is carried out and on-line tuning of the PI controller based on the proposed formulas is achieved which takes about 5 minutes, and then, the mean blood pressure regulation using the PI control system is continued in order to reduce the mean blood pressure to the desired value of 100 mmHg.

A detailed explanation of the simulation is given here. Figure 4 show the simulation results for the low sensitivity patient. Since this is for the low sensitive patient, it needs relatively higher infusion rate to reduce the blood pressure from 150 mmHg to 100 mmHg. Basically, the low sensitive patient has a smaller \( K \) in the continuous-time model (2). As the parameters given in Table 1 are for the discrete-time model with the sampling time of 15 sec., the coefficients \( b_i, i=1 \) and 2 are also small. In this simulation, the minimum sensitive parameters, \( a = 0.606, \ b^o = 0.053, \ b^i = 0.01, d_i = 2 \) (corresponding to \( T_i = 20 \) sec ) and \( d_2 = 2 \) are chosen. After 5 minutes the parameters of the patient’s model is identified and then, regulation of blood pressure starts. Note that pre-identification in this simulation is set by 5 minutes. In fact, it could be shorter than it. However, as we are more interested in the tuning algorithm, we will not further discuss on it. Note that the mean blood pressure of the patient can be reduced from the initial 150 mmHg to 100 mmHg within 5 minutes and be maintained. Since it is for the low

---

Figure 3. Variation of time-delay and its estimate.
sensitivity patient, the higher infusion rate of SNP is required.

Figure 5 shows the estimate of time delay $T_1$, time constant $\tau$, and sensitivity $K$, which are used in the PI controller tuning. This is for the low sensitive patient as considered in the simulation of Figure 4. It can be seen that the parameters are identified within 1.3 minutes. This implies that actual identification time at the beginning is not necessary be 5 minutes. The similar simulation results for the normal and high sensitivity patients can be also obtained.

Figure 6 shows the simulation results for the normal sensitive patient. According to Table 1, the normal sensitive patient has $a = 0.741$, $b_0 = 0.187$, $b_1 = 0.075$, $d_1 = 3$. Similarly, a pre-identification to determine the parameters is carried out. Then, the regulation of blood pressure from 150 mmHg to 100 mmHg is realized. Compared to the low sensitive case, the normal sensitive patient needs relatively small infusion rate. This is also reflected from the parameters of $b_i$, for $i=1$ and 2, which are higher. Figure 7 shows the simulation results for the high sensitive patient. It can be seen that as the patient has high sensitivity to the drug, a low infusion rate is needed to regulate blood pressure from 150 mmHg to 100 mmHg.

5. IMPLEMENTATION

The components used in the computerized drug delivery control system are shown in Figure 8. They are the controller system devices that have been selected from our design and implemented to regulate the patient’s MAP through the control of the infusion rate of SNP from the developed adaptive controller.

There are several devices involved in the implementation of the drug delivery system. For instance, syringe infusion pump, data acquisition card (PCMCIA card), blood pressure simulator, invasive blood pressure (IBP) sensor, IBP monitor and interface unit. PC or Notebook is a main centre controller of the drug delivery system. Blood pressure data will be sent to PC or notebook to do the analysis and manipulation, and then PC or notebook will issue the signal to change the syringe infusion pump speed accordingly to the infusion rate needed.
Figure 5. Estimation of parameters, $T_1$, $K$ and $\tau$ (low sensitivity).

Figure 6. Curve of MAP and infusion rate (normal sensitivity).
In the implementation, data acquisition PCMCIA card (Type 2) is used to capture real time blood pressure data. The chosen Data acquisition PCMCIA card modal is DAS16/16, which is manufactured by Measurement Computing. The card is able to meet the design requirements as stated above. The important features of this card are:

- 100 kS/sec sampling
- 16-bit A/D resolution
- 16 single-ended or eight differential analog inputs
- Programmable gain of 1, 2, 4, 8
- Four digital I/O channels
- 5µs max A/D conversion time
- From 4k sample FIFO via REPINSW, interrupt or software polled.

Figure 9 shows the set-up of the computerized control system. Application for a real testing is submitted for approval. We expect the real testing can be carried out with collaboration of clinical people in near future.

6. DISCUSSION AND CONCLUSION

Due to variable sensitivity and time delay in hypertension patients, it is difficult to achieve satisfactory control performance if infusion of the drug for management of hypertension in patients who have undergone major surgery, is adjusted manually by clinical personnel. Also, they may be often very busy with other tasks. The advantage offered by feedback control is obvious. It can generate a smoother regulation of blood pressure, and liberate clinical personnel from the tedious and time consuming work.

In general, design and analysis of control systems for time-varying systems are difficult and very often complex algorithms would be necessary for estimating the system parameters and also for on-line tuning of the controller. It is known that an accurate estimation of the system parameters, especially time-delay, is key for system stability and performance. In this paper, a novel adaptive PI controller has been proposed for blood pressure control of hypertension patients. To estimate time delay, an algorithm (Equation (9)) is proposed. Note that it is based on the parameters of the system identified, and therefore can be easily computed. Equations (15) and (16) are for estimation of the sensitivity and time constant. Using these, the PI controller can be easily tuned. The parameters of the system $b_j$ and $a_j$ of are identified using a least
Figure 8. Block diagrams of the major components of the adaptive control system.

Figure 9. Set-up of computerized control system.
squares algorithm. In practice, they can be initially selected as the values of normal patient model. Then, a further initial identification will be carried out to predetermine them.

The proposed adaptive PI control system has been simulated through the patient’ model with different drug sensitivities and time delays. The simulation results show that the proposed control system is effective for updating the change in the patient’s dynamics and for blood pressure regulation in the required time. However, a further clinical trial will be carried out in a near future. In fact, the tuning algorithm for estimating time delay proposed in this paper can also be applicable to other first-order time delays systems, which can be found especially in many industrial processes.

REFERENCES


AUTHOR INFORMATION

K. Y. Zhu graduated from Northeastern University, China, in 1982. He received his M.E. and Ph. D from University of Louvain-La-Neuve, in Belgium in 1986 and 1989, respectively. During 1991-1998, he was lecturer with School of Electrical and Electronic Engineering of Nanyang technological university (NTU), Singapore. Since 2001, he is associate professor with the school of EEE, NTU. His research interests are in the area of predictive control, process control and biomedical engineering.

H. Zheng received his B.E. from University of Science and Technology of China, M.E. degree from Nanyang Technological University, Singapore in 2005. Currently, he is a research and development engineer with Excelpoint Systems (Pte) Ltd.

D. G. Zhang received his B. E. degree in electrical engineering from Jilin University, M. E. degree in control engineering from Harbin Institute of Technology, and Ph.D. degree in electronic & electrical engineering from Nanyang Technological University in 2007. He is currently a research staff of Mechanical & Aerospace Engineering at Nanyang Technological University. His research interests are in the area of biomedical instrumentation, biological motor control, and rehabilitation engineering.