Blood Pressure Control Using Robust Backstepping Method During Surgical Operation

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Abstract: In order to maintain the blood pressure of the patient at a sufficiently low level during surgical operation, we designed a blood pressure control system. This paper considers uncertain parameters which exist in the blood pressure system. Therefore controlling blood pressure is done by robust control. The proposed method is based on robust backstepping method which we construct a robust control lyapunov function (rclf) and we will also provide a robustly stabilizing state feedback control law. As a result, the patients blood pressure is controlled. This paper reports the designing details of control system and the performance of the proposed method on blood pressure system has been shown.

Key words: Blood Pressure Control, Hypotensive Drug, Mean Arterial Pressure, Robust Backstepping Method, Uncertainty, Robust Control Lyapunov Function.

1. Introduction

Maintenance of blood pressure at a sufficiently low level above the critical limit during a surgical operation is of vital importance in many clinical situations such as Cardiac Surgery [1]. To keep the blood pressure at a normal level has several advantages in surgery. It reduces intraoperative bleeding and clearly reveals detailed anatomical structures in the operative field which otherwise might be obscured by blood thus facilitating a more accurate and speedy operation. The blood pressure of patients is controlled at a substantially low level during operation using a hypotensive drug such as trimethaphan camsilate.

By controlling the rate of infusion of hypotensive drug, the blood pressure of patients could be set at reference value. Also, the Mean Arterial pressure (in the following, abbreviated to MAP) is measured. The MAP of patient is maintained at approximately 60-80 mmHg, where the exact reference value of the MAP is determined by the medical doctor based on the condition of the patient.[2]

Since the late 1970's blood pressure control systems have been developed. Early research chiefly aimed at cardiovascular surgery postoperative blood pressure management. Sheppard used a modified PID controller, but this controller could not cope with individual differences of response to hypotensive drugs [3]. Adaptive control was applied by Widrow and Arnsparger et al, but these did not work well when disturbances existed [4, 5]. Koivo developed a blood pressure control system based on optimal control which kept the blood pressure at a low level, but the blood pressure range which could be set as the reference value was narrow[6]. Masuzawa and Fukui applied optimal control using an impulse identification method, and developed a blood pressure control system to keep pressure at a low level, but the controlling time of each experiment was shorter than 70 min [7]. Fukui and Masuzawa applied fuzzy logic to blood pressure control to keep blood pressure at a high level as a medical treatment for cancer, but oscillations could easily arise because the existence of the dead time in the response was not considered at the design stage [8].

This paper will focus on uncertain parameters which exist in the blood pressure system. Therefore controlling blood pressure is done by robust control. The methods described above are all non-robust that means the uncertainties and large variations of parameters are not considered.

In this paper, we propose a design procedure based on robust backstepping method which we construct a robust control lyapunov function (rclf) and we will also provide a robustly stabilizing state feedback control law. As a result, the patient's blood pressure is controlled.

In section 2, the dynamical model of blood pressure system is presented. The MAP control mechanism is explained together with its design process in section 3.

Simulation results are discussed in section 4. Conclusions are made in section 5.

2. Dynamical Model of Blood Pressure System

The purpose of our study is to control the blood pressure by a hypotensive drug; namely, the controlled variable y is MAP and the manipulating variable u is the infusion rate of the hypotensive drug. The dynamical model is describing the relation of y to u based on the dose response for the constant drug infusion. In the following, we explain modeling procedure:

Based on [9], the MAP's of two dogs infused with the hypotensive drug with constant rate measured. The infusion rates for each dog were set at 10, 20, 40 $\mu g/kg/\min$ and 40, 80, 160 $\mu g/kg/\min$, respectively. Typical response curves are shown in Fig.1.

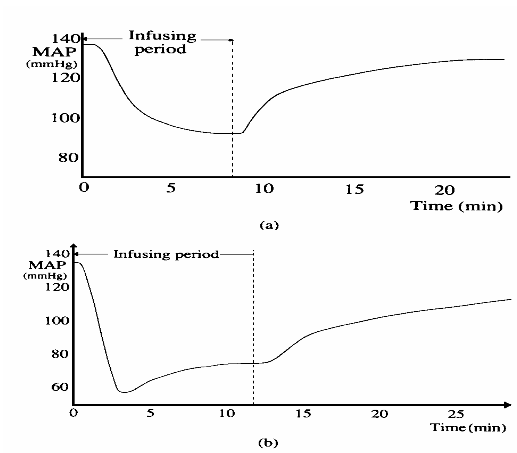


Fig.1: Dose response curves for trimethaphan camsilate

a) for small infusion rate
b) for large infusion rate

From dose data, it was estimated that the system includes:

1. a pure delay;
2. Some nonlinearity (or nonlinearities) of the saturating type; and
3. The dynamics in the non-saturating domain can be approximated by a first-order delay.

Based on the first and third estimations, we assumed the following dynamics:

$$\begin{cases} \dfrac{dx(t)}{dt} = -\dfrac{1}{T}x(t) + \dfrac{K}{T}u(t) \\ y = x(t-L) \end{cases} \tag{1}$$

Where $x(t)$ is a state variable, which corresponds to the MAP at $t+L$ in this case, T is a time-constant when MAP is decreasing, K is a gain, and L is a dead time.

From the second estimation, we assumed the next dynamics with a feedback with a dead zone for large infusion rates:

$$\begin{cases} \dfrac{dx(t)}{dt} = -\dfrac{1}{T}x(t) + \dfrac{K}{T}\left[u(t) - w(t)\right] \\ \dfrac{dw(t)}{dt} = x(t) - c \qquad ; \quad for \quad x(t) \ge c \\ y(t) = x(t-L) \end{cases} \tag{2}$$

Where $w(t)$ is a state of an integrator in the feedback loop, and c is the width of dead zone, which corresponds to the steady state value of MAP for large infusion rates.

These dynamics can be regarded as a simplified model of the rennin-angiotensin system which is activated when the arterial blood pressure falls below a threshold level [8]. It should be noted that the value of the integrator in the feedback loop must be reset when the MAP becomes higher than the steady state value of MAP for large infusion rates. Therefore, we added the element for resetting the integrator:

$$\frac{dw(t)}{dt} = -kw(t) \qquad ; \quad for \quad x(t) < c \tag{3}$$

Where k is a sufficiently large positive real number.

Since the model (1) can be included by the model (2), the following system can be obtained:

$$\begin{cases} \dfrac{dx(t)}{dt} = -\dfrac{1}{T}x(t) + \dfrac{K}{T}\left[u(t) - w(t)\right] \\ \dfrac{dw(t)}{dt} = \begin{cases} x(t) - c & ; \quad for \quad x(t) \ge c \\ -kw(t) & ; \quad for \quad x(t) < c \end{cases} \\ y(t) = x(t-L) \end{cases} \tag{4}$$

From the dose response of this model, the overshoots of the response were greater than the real response. So, a nonlinear function f is added to the model so that the overshoot is matched the real response. As a result, the model is obtained following:

$$\begin{cases} \dfrac{dx(t)}{dt} = -\dfrac{1}{T}x(t) + \dfrac{K}{T}\left[u(t) - w(t)\right] \\ \dfrac{dw(t)}{dt} = \begin{cases} x(t) - c & ; \quad for \quad x(t) \ge c \\ -kw(t) & ; \quad for \quad x(t) < c \end{cases} \\ y(t) = f(x(t-L)) \end{cases}$$

$$f(x) = \begin{cases} x & ; \quad for \quad x < c \\ c\left[\left(\dfrac{x}{c} - 1\right) + \left(\dfrac{1}{p}\right)^{\frac{p}{p-1}}\right]^{\frac{1}{p}} - c\left[1 - \left(\dfrac{1}{p}\right)^{\frac{1}{p-1}}\right] & ; \quad for \quad x \ge c \end{cases}$$

With $p = 4$ (5)

The ranges of parameters calculated are shown in table 1. [9]

Table 1: The Ranges of Model Parameters Obtained From Dose Responses

T	90 ~200 (s)
L	30 ~ 40 (s)
K	2.0 ~ 4.5 ($mmHg\ .kg\ .\min/\mu g$)
c	52 ~ 57 (mm)

From Table 1 we observe that T has large variations. Researchers have used Table 2 for their research work.

Table 2: The Determined Values of Model Parameters

L	40 (s)
K	4.5 ($mmHg.kg.\min/\mu g$)
c	54.5 (mm)

We take parameter T which has a large variation in design procedure and considering T as an uncertainty. We also use table 2 in the rest of the paper.

3. Design of Control System

In robust backstepping method, the class of uncertain nonlinear systems should be in strict feedback form. We consider a 2nd order system:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \phi_{11}(x,\omega) & \phi_{12}(x,\omega) \\ \phi_{21}(x,\omega) & \phi_{22}(x,\omega) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \phi_{23} \end{bmatrix} u + F(0,\omega) \tag{6}$$

for continuous scalar functions ϕ_{ij}. We assume that each function ϕ_{ij} depends only on ω and the state components x_1 through x_i. Let us now construct an rclf for a system in strict feedback form. We define a transformed state vector z as follows:

$$\begin{aligned} z_1 &= x_1 \\ z_2 &= x_2 - z_1 s_1(x_1) \end{aligned} \tag{7}$$

Smooth scalar functions $s_i(x_1,\ldots,x_i)$ which are to be determined in the recursive manner outlined below. Each function s_i will depend only on the state components x_1 through x_i. We show how to construct the functions s_i so that $V = z^T.z$ is an rclf for the system (6). We also provide a robustly stabilizing state feedback control law. But first we state the following theorem:

Theorem [10]: If the system (6) is in strict feedback form, then there exist suitable functions s_i such that $V = z^T.z$ is an rclf for the system.

Robustly stabilizing state feedback control law will be of the form $u(x) = z_n.s_n(x)$ where $s_n(x)$ another smooth function is yet to be determined.

Now, we apply the above theorem to the blood pressure system:

3.1. Stabilizing Problem:

3.1.1. when $x \geq c$:

If we assume $\frac{1}{T} = \omega$, as an uncertain parameter and $x_1 = w$, $x_2 = x$ as state variable, then from Eq.(5) we get:

$$\begin{aligned} \dot{x}_1 &= x_2 - 54.5 \\ \dot{x}_2 &= -4.5\ \omega\ x_1 - \omega\ x_2 + 4.5\ \omega\ u \end{aligned} \tag{8}$$

Comparing Eq. (6) and (8) we have:

$$\begin{aligned} &\phi_{11} = 0;\ \ \phi_{12} = 1;\ \ \phi_{21} = -4.5\omega;\ \ \phi_{22} = -\omega;\ \ \phi_{23} = 4.5\omega \\ &F_1(0,\omega) = -54.5 \end{aligned} \tag{9}$$

Now we explain a robustly stabilizing state feedback control law for the system.

First we consider M_1 as:

$$\mathrm{M}_1 = -c - 2\phi_{11} - 2\phi_{12}\, s_1(x_1) \tag{10}$$

By setting $c = 2 > 1$, we must choose $s_1(x_1)$ in order that M_1 becomes positive. (But M_1 and c will be introduced in the recursive manner.) Therefore by choosing $s_1(x_1) = -2 - x_1^2$, M_1 becomes positive.

From (7) we have:

$$z = S(x)\,x = \begin{bmatrix} 1 & 0 \\ -s_1 & 1 \end{bmatrix} x \tag{11}$$

$$x = S^{-1}(x) z = \begin{bmatrix} 1 & 0 \\ s_1 & 1 \end{bmatrix} z \tag{12}$$

So:

$$S(x) = \begin{bmatrix} 1 & 0 \\ 2 + x_1^2 & 1 \end{bmatrix} \tag{13}$$

Differentiating Eq. (11), we obtain:

$$\dot{z} = \begin{bmatrix} \frac{\partial S}{\partial x_1} x & \frac{\partial S}{\partial x_2} x \end{bmatrix} \dot{x} + S(x)\dot{x} = T(x)\dot{x} \tag{14}$$

Substituting the values of (9) in Eq. (14) we get:

$$T(x) = \begin{bmatrix} 1 & 0 \\ 2 + 3x_1^2 & 1 \end{bmatrix} \tag{15}$$

$$\dot{z} = \begin{bmatrix} 1 & 0 \\ 2 + 3x_1^2 & 1 \end{bmatrix} \dot{x} \tag{16}$$

We can use (12) to rewrite (6) as:

$$\dot{x} = \begin{bmatrix} \phi_{11} & \phi_{12} & 0 \\ \phi_{21} & \phi_{22} & \phi_{23} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ s_1 & 1 \\ 0 & s_2 \end{bmatrix} z + F(0,\omega) \quad (17)$$

Then:

$$\dot{x} = \begin{bmatrix} s_1 & 1 \\ -4.5\omega - \omega s_1 & -\omega + 4.5\omega s_2 \end{bmatrix} z + \begin{bmatrix} -54.5 \\ 0 \end{bmatrix} \quad (18)$$

By substituting (17) for $\dot{x}$ in (14) we obtain:

$$\dot{z} = T(x)\dot{x} = \begin{bmatrix} \phi_{11} + \phi_{12}s_1 & \phi_{12} \\ *_1 & *_1 + \phi_{23}s_2 \end{bmatrix} z + T(x)F(0,\omega) \quad (19)$$

Where $*_i$ denotes any function depending only on the disturbance ω, the states x_1 through x_i and the functions s_1 through s_i and their partial derivatives. So:

$$\begin{aligned} \dot{z} &= \begin{bmatrix} s_1 & 1 \\ (2+3x_1^2)s_1 - 4.5\omega - \omega s_1 & 2+3x_1^2 - \omega + 4.5\omega s_2 \end{bmatrix} z + T(x)\begin{bmatrix} -54.5 \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} 0 & 1 \\ (2+3x_1^2)s_1 - 4.5\omega - \omega s_1 & 2+3x_1^2 - \omega \end{bmatrix} z + \begin{bmatrix} s_1 & 0 \\ 0 & 4.5\omega s_2 \end{bmatrix} z + T(x)\begin{bmatrix} -54.5 \\ 0 \end{bmatrix} \end{aligned} \quad (20)$$

If we let $A(x,\omega)$ and $D(x,\omega)$ denote the first and second matrices in (20), respectively, then (20) becomes:

$$\dot{z} = [A(x,\omega) + D(x,\omega)]z + T(x)F(0,\omega) \quad (21)$$

We now calculate the derivative of $V(x) = z^T z$ as follows:

$$\dot{V} = z^T\left[A + A^T + 2D\right]z + 2F^T(0,\omega)T^T z \quad (22)$$

Using Young's inequality ($2ab \le a^2 + b^2$) on the last term in (22); we obtain:

$$\dot{V} \le z^T\left[A + A^T + 2D + TT^T\right]z + \|F(0,\omega)\|^2 \quad (23)$$

And from (15) we have:

$$\begin{aligned} T(x)T^T(x) &= \mathrm{I}_{2\times 2} + \begin{bmatrix} 0 & \otimes_1 \\ \otimes_1 & \otimes_1 \end{bmatrix} \\ &= \mathrm{I}_{2\times 2} + \begin{bmatrix} 0 & 2+3x_1^2 \\ 2+3x_1^2 & (2+3x_1^2)^2 \end{bmatrix} \end{aligned} \quad (24)$$

Note that a function of the type $\otimes_i$ is also of the type $*_i$, but the converse is not necessarily true because a $*_i$ function is allowed to depend on ω and x_{i+1}.

We combine (23) and (24) and use the definition of $A(x,\omega)$ from (20) and (21) to obtain:

$$\dot{V} \le z^T z + \|F(0,\omega)\|^2 + 2z^T D(x,\omega)z + z^T \begin{bmatrix} 2\phi_{11} & *_1 \\ *_1 & *_1 \end{bmatrix} z \quad (25)$$

Using the definition $D(x,\omega)$ from (20), it follows from (25) that:

$$\dot{V} \le -(c-1)z^T z - z^T M(x,\omega)z + \|F(x,\omega)\|^2 \quad (26)$$

Where the symmetric matrix $M(x,\omega)$ is given by:

$$M = \begin{bmatrix} -c - 2\phi_{11} - 2\phi_{12}s_1 & *_1 \\ *_1 & *_1 - 2\phi_{23}s_2 \end{bmatrix} \quad (27)$$

If we can choose the functions s_i such that this matrix $M(x,\omega)$ is positive definite then $\dot{V}$ becomes negative.

By comparing (24), (25) and (26), the matrix $M(x,\omega)$ becomes:

$$M(x,\omega) = -c\mathrm{I}_{2\times 2} - A - A^T - 2D - T_1 \quad (28)$$

Where $T.T^T = \mathrm{I}_{2\times 2} + T_1$. Substituting for (28); we get:

$$M(x,\omega) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad (29)$$

Where:

$$\begin{aligned} M_{11} &= -2 - 2s_1 \\ M_{12} = M_{21} &= -1 - (2+3x_1^2)(s_1+1) + 4.5\omega + \omega s_1 \\ M_{22} &= -6 - 6x_1^2 + 2\omega - (2+3x_1^2)^2 - 9\omega s_2 \end{aligned} \quad (30)$$

In order that $M(x,\omega)$ to be positive definite, each leading minor of $M(x,\omega)$ must be positive, means that:

$$-2 - 2s_1 > 0 \quad (31)$$

But we have assumed this relation in (10), also:

$$\begin{aligned} |M| = {} & (-2-2s_1)(-6-6x_1^2+2\omega-(2+3x_1^2)^2-9\omega s_2) \\ & -(-1-(2+3x_1^2)(s_1+1)+4.5\omega+\omega s_1)^2 \end{aligned} \quad (32)$$

We choose a smooth function s_2 so that the determinant of $M(x,\omega)$ is strictly positive. So, it is sufficient to take s_2 as follows:

$$\begin{aligned} s_2 < {} & \frac{1}{9\omega(2+2s_1)} + \frac{(-6-6x_1^2+2\omega-(2+3x_1^2)^2)}{9\omega} + \\ & \frac{(-1-(2+3x_1^2)(s_1+1)+4.5\omega+\omega s_1)^2}{9\omega(2+2s_1)} \end{aligned} \quad (33)$$

By considering s_2 as above, a robustly stabilizing state feedback law will be in the form $u = z_2 s_2$.

3.1.2. when $x<c$:

From Eq. (5) we observe that the equilibrium point is at the origin and state variable w exponentially tends to equilibrium point with time constant k that means:

$$w = e^{-kt} \quad (34)$$

Therefore, if we consider $u = \frac{1}{\omega K}\left(-x + \omega x + K\omega\ e^{-kt}\right)$, then all states tend to the origin so that stabilizing problem is guaranteed.

3.2. Tracking problem :

It is necessary that the output y (or MAP) to track reference value 80 mmHg that means y must tend to 80 mmHg. The reference value for output is $y^* = 80mmHg$. First, by neglecting the time delay (L) of the system, we design u by robust backstepping method and taking L=40[sec] at simulation step, which is negligible in most cardiovascular surgery.

Now we consider the design of control law:

3.2.1. when $x \ge c$:

By changing variables $\begin{cases} \varepsilon_1 = \omega + \frac{c}{k} \\ \varepsilon_2 = x - c \end{cases}$, the system equations are as follow:

$$\begin{cases} \dot{\varepsilon}_1 = \varepsilon_2 \\ \dot{\varepsilon}_2 = -K\omega\varepsilon_1 - \omega\varepsilon_2 + K\omega \ u \end{cases} \qquad (35)$$
$$y = c\left[\frac{\varepsilon_2}{c} + 0.1575\right]^{\frac{1}{4}} - 0.37c$$

To get $y^* = 80mmHg$, ε_2^* should tend to 613.25. So, we suggest a change of variable like $\begin{cases} \zeta_1 = \varepsilon_1 \\ \zeta_2 = \varepsilon_2 - 613.25 \end{cases}$. In this case, y or MAP reaches to a desired value of 80mmHg. By applying above change of variables to Eq.(35) we obtain:

$$\begin{cases} \dot{\zeta}_1 = 613.25 + \zeta_2 \\ \dot{\zeta}_2 = -4.5\omega\zeta_1 - \omega\zeta_2 + 4.5\omega u - 613.25\omega \end{cases} \qquad (36)$$

Eq. (36) is in strict feedback form, so we use robust backstepping method. By comparing these equation and Eq. (6) we have;

$$\phi_{11} = 0 \ ; \ \phi_{12} = 1 \ ; \ \phi_{21} = -4.5\omega \ ; \ \phi_{22} = -\omega \ ; \ \phi_{23} = 4.5\omega$$
$$F_1(0,\omega) = 613.25 \quad , \quad F_2(0,\omega) = -613.25\omega \qquad (37)$$

Using the design process which has explained in stabilizing section, we obtain the robustly state feedback control law as $u = z_2 s_2$. To get the desired value for output y, it is sufficient to take s_2 as follow:

$$s_2 < \frac{1}{9\omega(2+2s_1)} + \frac{(-6 - 6x_1^2 + 2\omega - (2+3x_1^2)^2)}{9\omega} + \frac{(-1-(2+3x_1^2)(s_1+1) + 4.5\omega + \omega s_1)^2}{9\omega(2+2s_1)} \qquad (38)$$

3.2.2. when $x<c$:

In this case, the equations of system are:

$$\begin{cases} \dot{x} = -\omega x - K\omega w + K\omega u \\ \dot{w} = -kw \end{cases} \qquad (39)$$
$$y = x$$

From (39), it is obvious that the state $w(t)$ exponentially tends to the origin with time constant k, which means:

$$w(t) = w(0)e^{-kt}$$

State x is the output of the system and should tend to $y^* = 80mmHg$. Thus, we assume the change of variables as follow:

$$\begin{cases} x_1 = w \\ x_2 = x - 80 \end{cases} \qquad (40)$$

So, we have:

$$\begin{cases} \dot{x}_1 = -kx_1 \\ \dot{x}_2 = -\omega(x_2 + 80) - K\omega x_1 + K\omega u \end{cases} \qquad (41)$$

By considering control law u as:

$$u = \frac{1}{K\omega}\left[\omega(x_2 + 80)\right] \qquad (42)$$

The state x (or output y) will tend to 80 mmHg.
According to the proposed design for the cases 3.2.1 and 3.2.2, the output y tends to the set value. The simulation results of the close-loop system in next section are investigated.

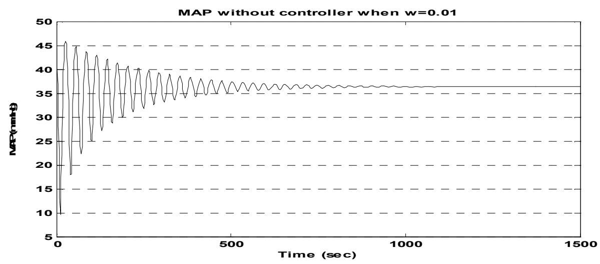
4. Simulation and results:

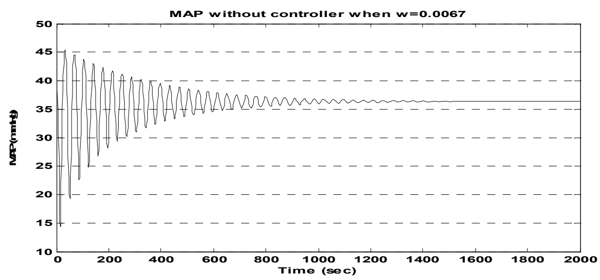
In this section, computer simulation results are presented. Results are based on two important factors: First, the MAP (or output y) should reach to the reference value with suitable time response. Second different values of uncertainties must not effect on output.
In this section, the results for three values of uncertainties (ω) are simulated which is given below:

$$T = 100,150,200 \quad \Rightarrow \omega = \frac{1}{T} = 0.01, 0.0067, 0.005$$

4.1. MAP without the controller

First, we simulate the system without using the controller. As it is shown in Fig.2, we observe that the MAP for three values of uncertainties has large variation. Also, the MAP has unsuitable time response. (MAP has large oscillations, the settling time is long and overshoot is large.)





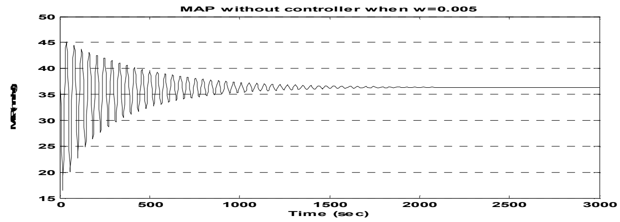


Fig. 2 :MAP without the controller

4.2. MAP with the controller:

In this case, by applying the designed controller to the system, for three values of uncertainties, the MAP is shown in Fig. 3. It is obvious that the MAP tracks the set value with an appropriate settling time (less than one second) and without any oscillation or overshoot. Also, the MAP is constant under changes of ω or equivalently T.

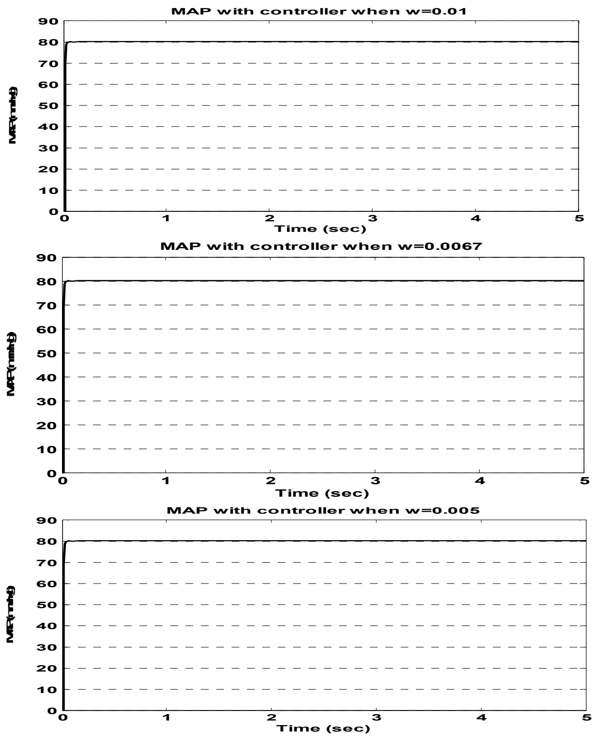


Fig. 3: MAP with the controller

In design process, we have not considered the time delay $L=40^{sec}$. Knowing that the MAP of the controlled system reaches to set value in less than one second, if we consider $L=40^{sec}$, the MAP reaches the set value in 40^{sec} approximately. But this is negligible in most cardiovascular surgery.

5. Conclusions:

In order to maintain the blood pressure of a patient at a substantially low level during surgical operation, we designed a blood pressure control system based on robust backstepping method. First we designed a controller without considering the time delay and assume the time constant T which has the most variations as uncertainty. Simulation results show that the MAP tracks the set value with an appropriate settling time (less than one second) and without any oscillation or overshoot.

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