Heartbeat ECG Tracking Systems Using Observer Based Nonlinear Controller

Mina Ali Akbar Semnani[1], Ahmad Reza Vali[2], Seyed Mahdi Hakimi[1], Vahid Behnamgol[3*]

Abstract – In this paper, an observer based sliding mode method is used to control the heart rhythm system. For this purpose, nonlinear and uncertain dynamics of a sick human heart are considered. The control signals applied to the three points of the heart are determined in such a way that the electrocardiogram signal behaves desirable. An observer is also used to estimate state variables and uncertain functions. Continuous approximation method has been used to remove chattering. The simulation results show the good performance of the proposed control system.

Keywords: Heartbeat, Electrocardiogram Signal, Sliding Mode Controller, Extended State Observer.

1. Introduction

Normal cardiac function depends on the adequate timing of excitation and contraction in the various regions of the heart and on an appropriate pacemaker rate. This complex task is implemented by the highly specialized electrical properties of the various elements of the heart system, including the sinoatrial node (SA), atria, atrioventricular node (AV), His-Purkinje conducting system, and ventricles [1].The pacemaker cells of the cardiac sinoatrial node (SAN) are essential for normal cardiac automaticity. Dysfunction in cardiac pacemaking results in human sinoatrial node dysfunction (SND). SND more generally occurs in the elderly population and is associated with impaired pacemaker function causing abnormal heart rhythm [2].

Nowadays, the use of new control theories to control medical systems and various diseases has become popular. Disease behavior can be improved with high accuracy by using control methods.Considering the dynamics of a patient's heart as a controlled process, the use of new control theories can be useful for tracking the desired heart rhythms.

In [3, 4] the Van der pol nonlinear equations are used to model the three main parts of the heart. In this reference, the effect of three parts on each other is modeled by using time delay equations. In addition, second-order nonlinear equations are used to model the ECG signal. In [5, 6] robust and PID strategies are used to control of heart rate. In addition to, controlling the heart rate is the goal, but controlling the behavior of the ECG signal is not intended. The method used in this reference is one of the linear control methods that requires a linearization of the system around the operating point for design. One of the disadvantages of this method reduces controller performance by keeping the system away from the operating point and does not guarantee resistance to parametric and non-parametric uncertainties.

Reference [7] a nonlinear feedback based on observer is designed to track the normal ECG signal. One of the controller problems in this reference is the lack of robustness of the control system in the presence of uncertainties.

In [8], an adaptive controller has been used to the heart rate control of a wheelchair user. In [9], the linear feedback method is used to control a circulating pump simulator. [10] uses linear feedback to control heart rate. In [11], a robust control method is used to adjust heart rate and synchronize the two chaotic parts of SA and AV.

The innovation of this paper is the use of an observer based nonlinear controller to control the behavior of the ECG signal. The controller will also be designed with a nonlinear and robust sliding mode control (SMC) theory. In the conventional SMC, for the sliding surface to be stable, a switching function has to be used in the control law, which causes chattering of the control signals. The chattering problem in sliding mode control is one of the most common

1 Department of Electrical Engineering, Damavand Branch, Islamic Azad University, Damavand, Iran.
2-MalekAshtar University of Technology, Tehran, Iran
3* Corresponding Author: Malek Ashtar University of Technology, Tehran, Iran. Email: vahidbehnamgol@gmail.com

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handicaps for applying to real applications. Chattering is a result to low control accuracy. It may also excite unmodeled high frequency dynamics and may even lead to instability. One approach to eliminate chattering in control signal is to use the continuous approximation method. In this method within the boundary layer near the sliding surface, the discontinuous switching function is interpolated by a continuous function to avoid discontinuity of the control signals [12]. Another innovation of this paper is the use of an observer to estimate unmeasurable states and functions.

In the second section, dynamic system modeling on heart rhythm will be performed. In the third section, the controller is designed to track the normal ECG signal by using an observer based sliding mode method controller. In the fourth section, with numerical simulation, the performance of the proposed controller in controlling the ECG behavior is examined and finally we conclude.

2. Dynamic model of heart rate system

Heart rate modeling has been performed to analyze and control diseases using different methods. In reference [3] the behavior of the three parts of SA, AV and HP of the heart is modeled. Van der pol equations are used to model natural and medical phenomena. In the modeling, the effect on the SA part of the AV behavior and the effect of the AV part on the HP behavior is considered using time delay statements. Although this model simulates the electrical behavior of the three parts of the heart well, butdoes not adapt to the real ECG signal behavior. Also, in this model, the position of the effect of the external signal is not specified. In reference [4] similar to reference [3], the Van der pol nonlinear equations are used to model the three main parts of the heart. The general form of the electrical system of the heart is shown in Figures (1) and (2). Fig (2) shows how to produce P, Ta, QRS and T waves using the outputs of the three main sections. Eventually the ECG signal will be generated by combining these waves.

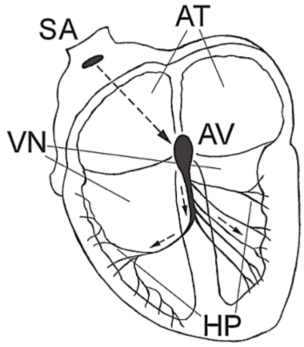

Fig. 1- Cardiac conduction system[3]

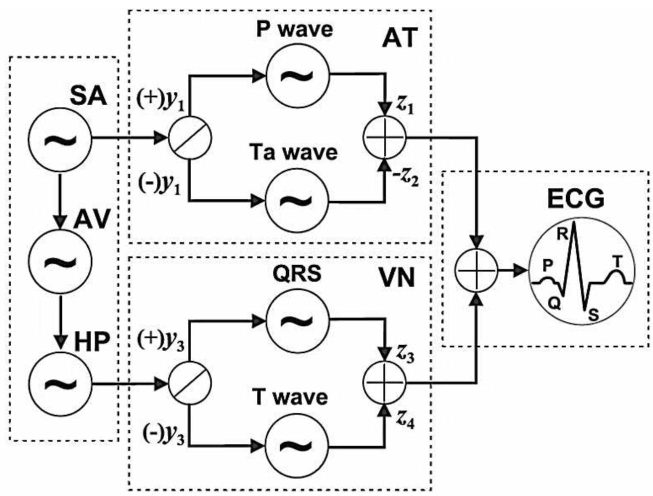

Fig. 2 – General scheme of the heart model[3]

In [11], the proposed model for the three main parts of the heart is shown in Equation (1).

$$SA:\begin{cases}\dot{x}_1 = y_1\\ \dot{y}_1 = -a_1 y_1(x_1-u_{11})(x_1-u_{12}) - f_1 x_1(x_1+d_1)(x_1+e_1)+u_1\end{cases}$$
$$AV:\begin{cases}\dot{x}_2 = y_2\\ \dot{y}_2 = -a_2 y_2(x_2-u_{21})(x_2-u_{22}) - f_2 x_2(x_2+d_2)(x_2+e_2)+k_{SA-AV}(y_1^{\tau_{SA-AV}}-y_2)+u_2\end{cases}$$
$$HP:\begin{cases}\dot{x}_3 = y_3\\ \dot{y}_3 = -a_3 y_3(x_3-u_{31})(x_3-u_{32}) - f_3 x_3(x_3+d_3)(x_3+e_3)+k_{AV-HP}(y_2^{\tau_{AV-HP}}-y_3)+u_3\end{cases} \quad (1)$$

$y_i^{\tau} = y_i(t-\tau)$ and τ are the time delay and $u = \begin{bmatrix}u_1 & u_2 & u_3\end{bmatrix}^T$ is the control input vector. Figure (3) is the basis for the construction of the ECG signal. With this explanation, relation (2):

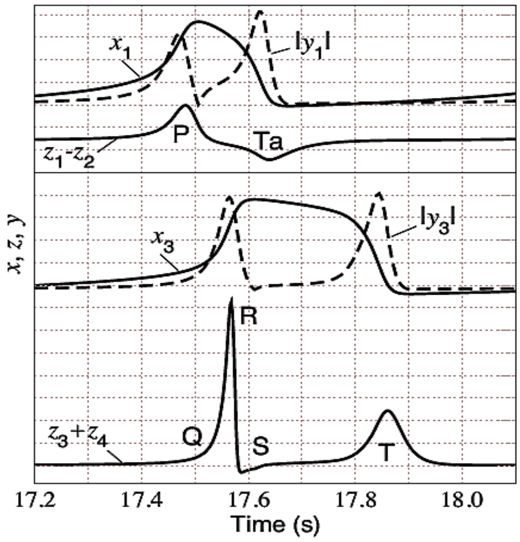

Fig. 3 – Coupling between pacemakers and muscles. Calculated action potentials (x_i), absolute value of their derivatives (y_i), and muscle response (z_i) for sinoatrial pacemaker and atrium muscle (top panel), and His–Purkinje pacemaker and ventricular muscle (bottom panel). [3]

(2)

$$P\ wave: \begin{cases} \dot z_1 = k_1(-c_1 z_1(z_1 - w_{11})(z_1 - w_{12}) - b_1 v_1 - d_1 v_1 z_1 + I_{AT_{De}}) \\ \dot v_1 = k_1 h_1 (z_1 - g_1 v_1) \end{cases}$$

$$Ta\ wave: \begin{cases} \dot z_2 = k_2(-c_2 z_2(z_2 - w_{21})(z_2 - w_{22}) - b_2 v_2 - d_2 v_2 z_2 + I_{AT_{Re}}) \\ \dot v_2 = k_2 h_2 (z_2 - g_2 v_2) \end{cases}$$

$$QRS\ wave: \begin{cases} \dot z_3 = k_3(-c_3 z_3(z_3 - w_{31})(z_3 - w_{32}) - b_3 v_3 - d_3 v_3 z_3 + I_{VN_{De}}) \\ \dot v_3 = k_3 h_3 (z_3 - g_3 v_3) \end{cases}$$

$$T\ wave: \begin{cases} \dot z_4 = k_4(-c_4 z_4(z_4 - w_{41})(z_4 - w_{42}) - b_4 v_4 - d_4 v_4 z_4 + I_{VN_{Re}}) \\ \dot v_1 = k_4 h_4 (z_4 - g_4 v_4) \end{cases}$$

$I_{AT_{De}}$, $I_{AT_{Re}}$, $I_{VN_{De}}$, and $I_{VN_{Re}}$ are defined as Equation (3) to influence the output of the dynamics of the three parts of the heart.

(3)

$$I_{AT_{De}} = \begin{cases} 0 & for\ \ y_1 \le 0 \\ k_{AT_{De}} y_1 & for\ \ y_1 > 0 \end{cases}$$

$$I_{AT_{Re}} = \begin{cases} k_{AT_{Re}} y_1 & for\ \ y_1 \le 0 \\ 0 & for\ \ y_1 > 0 \end{cases}$$

$$I_{VN_{De}} = \begin{cases} 0 & for\ \ y_3 \le 0 \\ k_{VN_{De}} y_3 & for\ \ y_3 > 0 \end{cases}$$

$$I_{VN_{Re}} = \begin{cases} k_{VN_{Re}} y_3 & for\ \ y_3 \le 0 \\ 0 & for\ \ y_3 > 0 \end{cases}$$

According to Figure (3) to construct the ECG signal from Equation (4):

$$ECG = z_0 + z_1 + z_2 + z_3 + z_4 \quad (4)$$

$z_0 = 0.2$ is selected to adjustment the ECG signal reference line. Therefore, in this reference, the ECG signal behavior and the three main parts of the heart are completely modeled. To simulate a normal ECG f1 = 22, tachycardia disease f1 = 87 and bradycardia disease f1 = 13 are considered.

3. Controller design

The system has three separate inputs, so the controller must be designed as a vector. First, the standard sliding mode controller is designed as a vector. Then, the extended state observer is designed to estimate unmeasurable information. Finally, to prevent the chattering phenomenon and to produce a smooth control signal, the continuous approximation method is used.

3.1. Sliding mode controller

Using the sliding mode method to design the heart rate control system, the output vector for the three main parts of the heart is as follows:

$$y = \begin{bmatrix} y_{SA} & y_{AV} & y_{HP} \end{bmatrix}^T = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T \quad (5)$$

Sliding variable vector:

$$\begin{bmatrix} s_{SA} \\ s_{AV} \\ s_{HP} \end{bmatrix} = \begin{bmatrix} \dot{e}_{SA} + \lambda_{SA} e_{SA} \\ \dot{e}_{AV} + \lambda_{AV} e_{AV} \\ \dot{e}_{HP} + \lambda_{HP} e_{HP} \end{bmatrix} \quad (6)$$

Error vector:

$$\begin{bmatrix} e_{SA} \\ e_{AV} \\ e_{HP} \end{bmatrix} = \begin{bmatrix} y_{SA} - y_{SA_{ref}} \\ y_{AV} - y_{AV_{ref}} \\ y_{HP} - y_{HP_{ref}} \end{bmatrix} \quad (7)$$

Sliding variable dynamics can be calculated as follow:

$$\begin{bmatrix} \dot{s}_{SA} \\ \dot{s}_{AV} \\ \dot{s}_{HP} \end{bmatrix} = \begin{bmatrix} \ddot{e}_{SA} + \lambda_{SA} \dot{e}_{SA} \\ \ddot{e}_{AV} + \lambda_{AV} \dot{e}_{AV} \\ \ddot{e}_{HP} + \lambda_{HP} \dot{e}_{HP} \end{bmatrix}$$
$$= \begin{bmatrix} -a_1 y_1 (x_1 - u_{11})(x_1 - u_{12}) - f_1 x_1 (x_1 + d_1)(x_1 + e_1) - \ddot{y}_{SA_{ref}} + \lambda_{SA} \dot{e}_{SA} \\ -a_2 y_2 (x_2 - u_{21})(x_2 - u_{22}) - f_2 x_2 (x_2 + d_2)(x_2 + e_2) + k_{SA-AV} (y_1^{\tau_{SA-AV}} - y_2) - \ddot{y}_{AV_{ref}} + \lambda_{AV} \dot{e}_{AV} \\ -a_3 y_3 (x_3 - u_{31})(x_3 - u_{32}) - f_3 x_3 (x_3 + d_3)(x_3 + e_3) + k_{AV-HP} (y_2^{\tau_{AV-HP}} - y_3) - \ddot{y}_{HP_{ref}} + \lambda_{HP} \dot{e}_{HP} \end{bmatrix}$$
$$+ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (8)$$

For this system, Lyapunov functions are considered as follows:

$$V_i = \frac{1}{2} s_i^2 \quad , \quad i = \{1, 2, ..., m\} \quad (9)$$

To guarantee finite time convergence

$$\dot{V} = \frac{\partial V}{\partial s} \dot{s} = s \dot{s} \le -\eta |s| \quad (10)$$

the control input can be designed as follows:

(11)

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} u_{eq_{SA}} - k_{SA} sign(s_{SA}) \\ u_{eq_{AV}} - k_{AV} sign(s_{AV}) \\ u_{eq_{HP}} - k_{HP} sign(s_{HP}) \end{bmatrix} = \begin{bmatrix} u_{eq_{SA}} - k_{SA} sign\left(y_1 - \dot{y}_{SA_{ref}} + \lambda_{SA}\left(x_1 - y_{SA_{ref}}\right)\right) \\ u_{eq_{AV}} - k_{AV} sign\left(y_2 - \dot{y}_{AV_{ref}} + \lambda_{AV}\left(x_2 - y_{AV_{ref}}\right)\right) \\ u_{eq_{HP}} - k_{HP} sign\left(y_3 - \dot{y}_{HP_{ref}} + \lambda_{HP}\left(x_3 - y_{HP_{ref}}\right)\right) \end{bmatrix}$$

$\ddot{y}_{SA_{ref}}$, $\ddot{y}_{AV_{ref}}$, $\ddot{y}_{HP_{ref}}$ are second-order derivatives of desirable outputs. u_{eq} is also equivalent control:

(12)

$$\begin{bmatrix} u_{eq_{SA}} \\ u_{eq_{AV}} \\ u_{eq_{HP}} \end{bmatrix} = \begin{bmatrix} a_1 y_1 (x_1 - u_{11})(x_1 - u_{12}) + f_1 x_1 (x_1 + d_1)(x_1 + e_1) + \ddot{y}_{SA_{ref}} - \lambda_{SA}\dot{e}_{SA} \\ a_2 y_2 (x_2 - u_{21})(x_2 - u_{22}) + f_2 x_2 (x_2 + d_2)(x_2 + e_2) - k_{SA-AV}(y_1^{\tau_{SA-AV}} - y_2) + \ddot{y}_{AV_{ref}} - \lambda_{AV}\dot{e}_{AV} \\ a_3 y_3 (x_3 - u_{31})(x_3 - u_{32}) + f_3 x_3 (x_3 + d_3)(x_3 + e_3) - k_{AV-HP}(y_2^{\tau_{AV-HP}} - y_3) + \ddot{y}_{HP_{ref}} - \lambda_{HP}\dot{e}_{HP} \end{bmatrix}$$

By using an extended state observer, the controller (11) can be replaced by:

(13)

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} \hat{F}_{SA} + \ddot{y}_{SA_{ref}} - \lambda_{SA}\left(\hat{y}_1 - \dot{y}_{SA_{ref}}\right) - k_{SA} sign\left(\hat{y}_1 - \dot{y}_{SA_{ref}} + \lambda_{SA}\left(x_1 - y_{SA_{ref}}\right)\right) \\ \hat{F}_{AV} + \ddot{y}_{AV_{ref}} - \lambda_{AV}\left(\hat{y}_2 - \dot{y}_{AV_{ref}}\right) - k_{AV} sign\left(\hat{y}_2 - \dot{y}_{AV_{ref}} + \lambda_{AV}\left(x_2 - y_{AV_{ref}}\right)\right) \\ \hat{F}_{HP} + \ddot{y}_{HP_{ref}} - \lambda_{HP}\left(\hat{y}_3 - \dot{y}_{HP_{ref}}\right) - k_{HP} sign\left(\hat{y}_3 - \dot{y}_{HP_{ref}} + \lambda_{HP}\left(x_3 - y_{HP_{ref}}\right)\right) \end{bmatrix}$$

3.2. Extended state observer

Consider a nonlinear system as follows:

(14)

$$\dot{x} = y$$
$$\dot{y} = F(x, y) + u$$

where x and y are the state variables, $F(x, y)$ is the nonlinear function and u is the control input. The state variable x can only be measured. An observer is defined as follows in reference:

(15)

$$\dot{\hat{x}} = \hat{y} + \beta_1 e$$
$$\dot{\hat{y}} = \hat{F} + u + \beta_2 fal(e, \alpha_1, \delta)$$
$$\dot{\hat{F}} = \beta_3 fal(e, \alpha_2, \delta)$$
$$e = x - \hat{x}$$

e is the estimation error, β_1, β_2, β_3 are the observer adjustment parameters, $\hat{x}$, $\hat{y}$, $\hat{F}$ are the estimation of the variables x, y, F. The $fal(e, \alpha, \delta)$ function is also defined as follows[13]:

(16)

$$fal(e, \alpha, \delta) = \begin{cases} \dfrac{e}{\delta^{1-\alpha}}, & |e| \le \delta \\ |e|^{\alpha} sign(e), & |e| > \delta \end{cases}$$

State variables, indefinite and immeasurable functions that related to the three main parts of the heart will be estimated using this observer as follows.

(17)

$$SA_{Dynamic}:\begin{cases}\dot{x}_1 = y_1\\ \dot{y}_1 = F_{SA} + u_1\end{cases}$$

$$SA_{Observer}:\begin{cases}\dot{\hat{x}}_1 = \hat{y}_1 + \beta_{1_{SA}} e_1\\ \dot{\hat{y}}_1 = \hat{F}_{SA} + u_1 + \beta_{2_{SA}} fal(e_1, \alpha_{1_{SA}}, \delta_{SA})\\ \dot{\hat{F}}_{SA} = \beta_{3_{SA}} fal(e_1, \alpha_{2_{SA}}, \delta_{SA})\end{cases}$$

$$e_1 = x_1 - \hat{x}_1$$

$$AV_{Dynamic}:\begin{cases}\dot{x}_2 = y_2\\ \dot{y}_2 = F_{AV} + u_2\end{cases}$$

$$AV_{Observer}:\begin{cases}\dot{\hat{x}}_2 = \hat{y}_2 + \beta_{1_{AV}} e_2\\ \dot{\hat{y}}_2 = \hat{F}_{AV} + u_2 + \beta_{2_{AV}} fal(e_2, \alpha_{1_{AV}}, \delta_{AV})\\ \dot{\hat{F}}_{AV} = \beta_{3_{AV}} fal(e_2, \alpha_{2_{AV}}, \delta_{AV})\end{cases}$$

$$e_2 = x_2 - \hat{x}_2$$

$$HP_{Dynamic}:\begin{cases}\dot{x}_1 = y_1\\ \dot{y}_1 = F_{HP} + u_1\end{cases}$$

$$HP_{Observer}:\begin{cases}\dot{\hat{x}}_3 = \hat{y}_3 + \beta_{1_{HP}} e_3\\ \dot{\hat{y}}_3 = \hat{F}_{HP} + u_3 + \beta_{2_{HP}} fal(e_3, \alpha_{1_{HP}}, \delta_{HP})\\ \dot{\hat{F}}_{HP} = \beta_{3_{HP}} fal(e_3, \alpha_{2_{HP}}, \delta_{HP})\end{cases}$$

$$e_3 = x_3 - \hat{x}_3$$

4. Simulation results

This section presents the simulation results. To simulate the SA, AV, HP and ECG parts of the model, the parameter values are considered as tables (1) and (2).

Table 1- Parameter values in simulation of SA, AV and HP sections [3]

Parameter	Value	Parameter	Value	
f_2	8.4	a_1	40	
f_3	1.5	a_2	50	
d_1	3	a_3	50	
d_2	3	u_{11}	0.83	
d_3	3	u_{21}	0.83	
e_1	3.5	u_{31}	0.83	
e_2	5	u_{12}	-0.83	
e_3	12	u_{22}	-0.83	
k_{SA_AV}	f_1	u_{32}	-0.83	
k_{AV_HP}	f_1	f_1	22	normal
			87	Tachycardia
			15	Bradycardia

Table 2 - Parameter values in ECG section simulation [3]

Parameter	Value	Parameter	Value
h_1	0.004	k_1	2000
h_2	0.004	k_2	400
h_3	0.008	k_3	10000
h_4	0.008	k_4	2000
g_1	1	c_1	0.26
g_2	1	c_2	0.26
g_3	1	c_3	0.12
g_4	1	c_4	0.1
ω_{11}	0.13	b_1	0
ω_{21}	10	b_2	0
ω_{31}	10	b_3	0.015
ω_{41}	0.19	b_4	0
ω_{12}	0.12	d_1	0.4
ω_{22}	1.1	d_2	0.4
ω_{32}	0.22	d_3	0.09
ω_{42}	0.8	d_4	0.1

Here we study the performance of the observer based sliding mode controller. In this method, an observer is used to estimate state variables and nonlinear functions. The observer performance can be seen in Figures (4) to (6) by estimating the unmeasurable state variables and nonlinear functions.

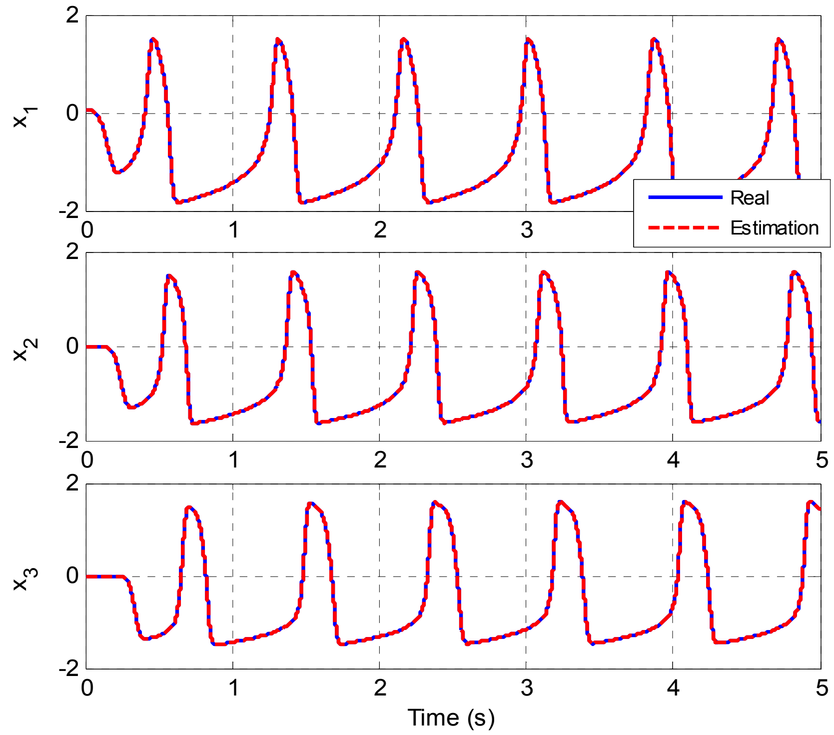

Fig. 4- Estimation of the SA, AV nodes and HP outputs

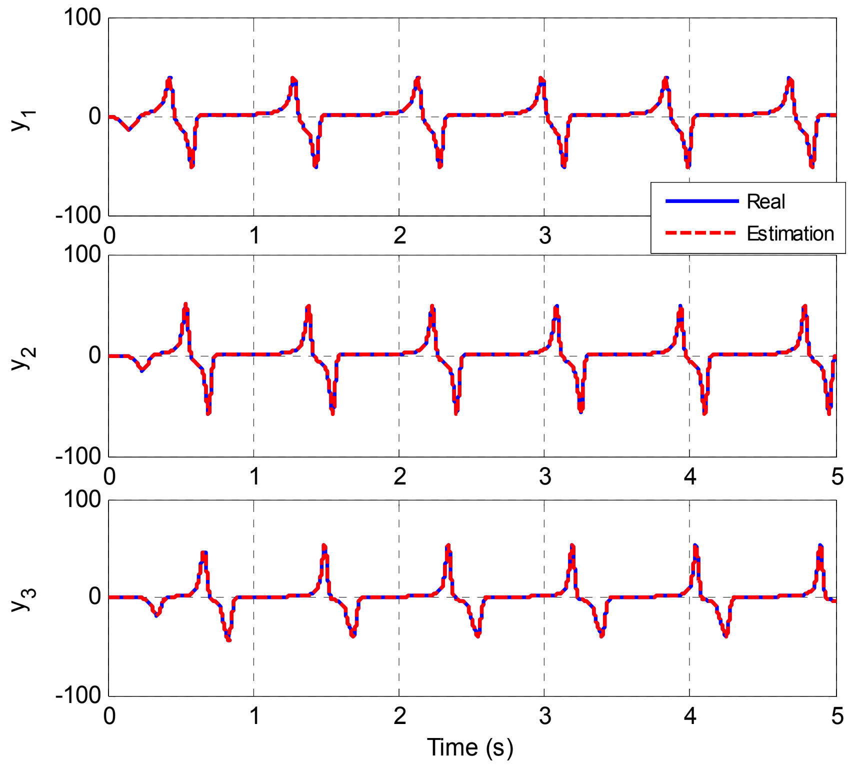

Fig. 5- Estimation of the SA, AV nodes and HP unmeasurable variables

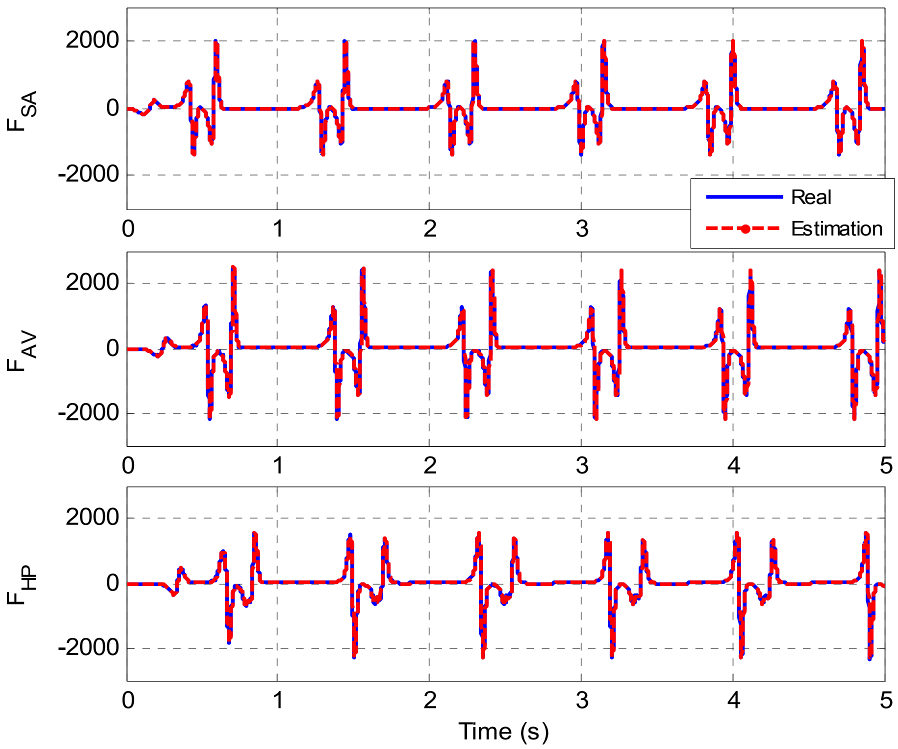

Fig. 6- Estimation of unmeasurable functions

By applying observer based sliding mode controller to the model of a human heart, changes in the ECG signal compared to the reference ECG is plotted in Figure (7).

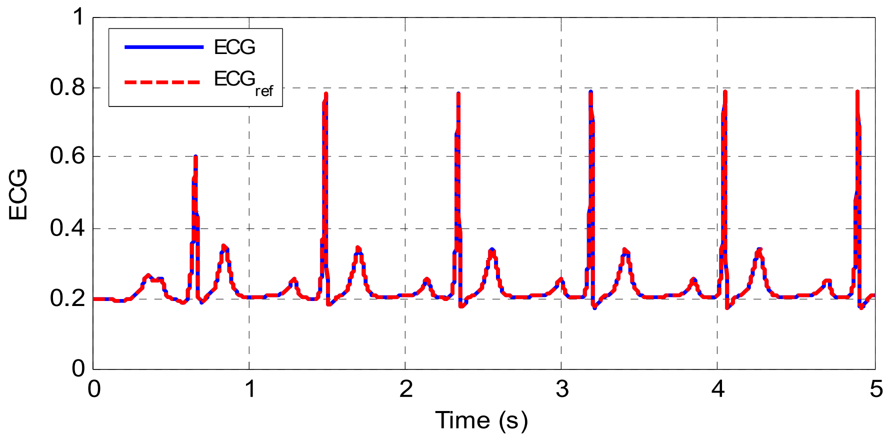

Fig. 7- ECG signal tracking

In (8)the behavior of the SA, AV and HP sections is traced by using the observer based sliding mode controller with high accuracy.

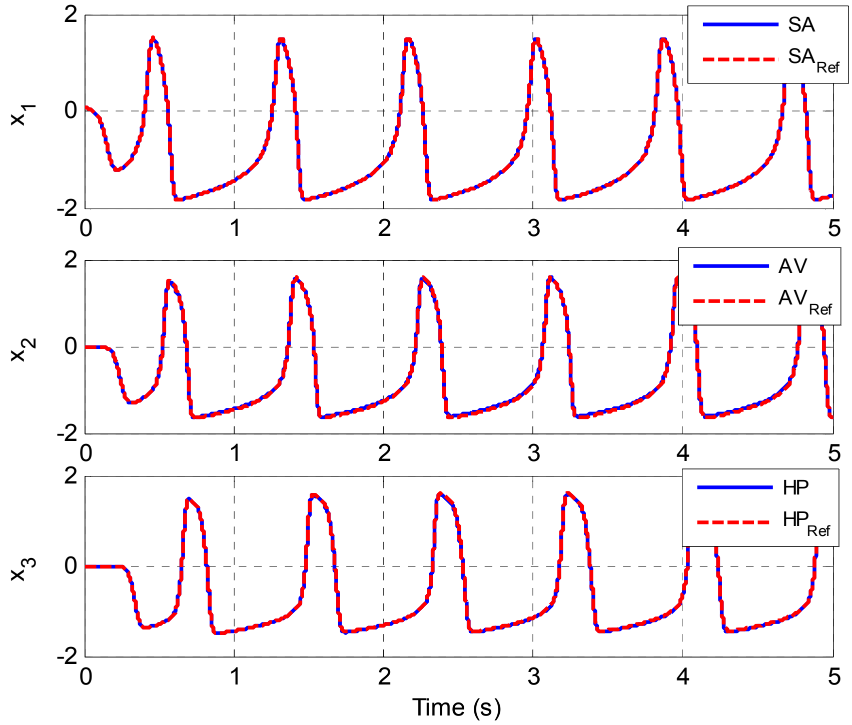

Fig. 8- Tracking the behavior of SA, AV nodes and HP system

Figure (9) show the curves related to the control signal applied to the patient's heart model. It can be seen that due to the use of the continues approximation method, the control input signals are without chattering.

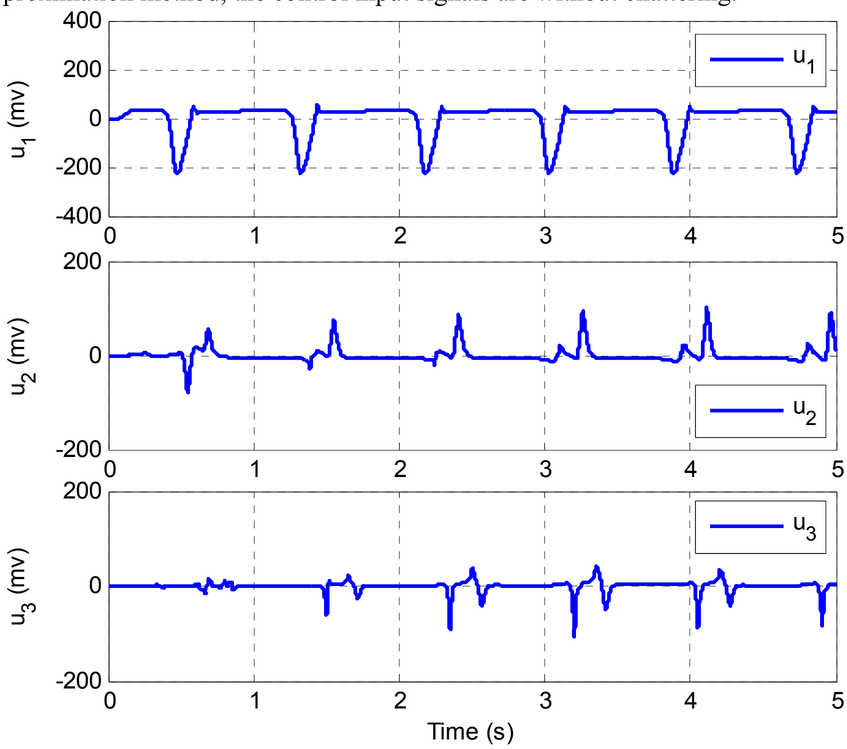

Fig. 9 - Control input signals

5. Conclusion

In this paper, a vector observer based sliding mode controller was designed to control the ECG signal behavior.

We designed the controller as a vector and used the continues approximation method to remove the chattering. By applying the proposed controller, the reference signal was tracked with good accuracy. We also saw that the observer estimates the state variables and nonlinear unmeasurable functions with high accuracy and good speed and provides them to the controller. The sliding variables converge to zero with high accuracy and due to the use of the continues approximation method, the control input signals can be implemented without chattering.

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