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Event-triggered reliable synchronization of chaotic coronary artery system

Abstract. *This paper studies the problem of synchronization for chaotic coronary artery system. The heart receives its oxygen and nourishment from the blood vessel namely coronary artery. Furthermore, due to some uncertain factors such as high blood pressure, thyroid, heart disorders, and others can cause the inner pressure and diameter of the coronary artery vessel to change, resulting in an aberrant pulse. In order to synchronize affected system with healthy system, event -triggered reliable controller is designed with the aid of linear matrix inequalities. Finally, simulations are performed to ensure that the developed controller is successful.*

Streszczenie. *Niniejsza praca dotyczy problemu synchronizacji chaotycznego układu tętnic wieńcowych. Serce otrzymuje tlen i pożywienie z naczynia krwionośnego, czyli tętnicy wieńcowej. Co więcej, z powodu pewnych niepewnych czynników, takich jak wysokie ciśnienie krwi, choroby tarczycy, serca i inne, mogą powodować zmianę wewnętrznego ciśnienia i średnicy naczynia wieńcowego, co skutkuje nieprawidłowym tętnem. Aby zsynchronizować uszkodzony system ze zdrowym systemem, niezawodny sterownik wyzwalany zdarzeniami został zaprojektowany z wykorzystaniem liniowych nierówności macierzy. Na koniec przeprowadzane są symulacje, aby upewnić się, że opracowany sterownik odniesie sukces.* **(Wyzwalana zdarzeniem niezawodna synchronizacja chaotycznego układu tętnic wieńcowych)()**

Keywords: Coronary artery system, synchronization, Event- triggered control, Reliable control
Słowa kluczowe: tętnienia wieńcowe serca, synchronizacja, układ chaotyczny

Introduction

Due to its vast range of applications in many practical contexts such as biology, electronics, economics, finance, and so on, the synchronization of chaos behavior of system states has gained great attention among many investigators in recent decades [1, 2, 3, 4, 5]. The coronary artery is the blood vessel that provides the heart with nutrition and oxygen. Several unpredictable factors such as anomalies of the heart, ectopic pacemakers, thyroid disease, excessive blood pressure, irregular dynamic phenomena, and heart-valve disorders might affect the inner pressure and width of the channel. As a result, a healthy coronary artery vessel is critical for controlling arrhythmia's; otherwise, cardiac arrest and even death may result. The mathematical model is specifically constructed to reflect nonlinear behavior and chaotic motions in the coronary artery vessel in order to analyze the CACS spectrum. CACS, on the other hand, is critical to human existence because it ensures that the heart receives enough nutrients and oxygen at all times of the day and night. As a result, the system's health is essential. As a result, the researchers spent a lot of time designing alternative control protocols for the coronary artery chaos system in order to mitigate the impacts. The synchronization of diseased CACS to its healthy system is maintained with the aid of several synchronization methodologies such as adaptive control, H_∞ control, state-feedback control, and sliding-mode control addressed in the existing literature [6, 7, 8, 9, 10]. In [7], synchronization problem for the uncertain coronary artery system with time-delay and input saturation was considered. H_∞ synchronization control problem for coronary artery system with input time varying delay has been investigated in [8].

In reality, abnormalities arise from a variety of sources, and treatment effectiveness cannot be guaranteed all of the time. Because of the defects in the actuator, the dynamics of the system are not effectively regulated by the control input signals. Due to this reason, the researcher's paid more attention on reliable control technique [11, 12, 13]. Furthermore, errors and risks may occur in a non-deterministic manner, occurring at any point in time for any human, resulting in unanticipated performance degradation. In order to accept treatment flaws and dangers, the reliable control strategy is adopted.

The event-triggered control system was implemented to prevent control waste [14, 15, 16, 17]. Control signals are only sent when the specified conditions are met in this sort of controller. On the other hand, therapeutic delays can have a significant impact on human life and even result in death. The system's performance is further harmed by delays in medicine consumption and drug absorption, which can dramatically increase the risk of human life. As a result, therapeutic delays are taken as input delays. To save a human life, it is critical to forecast and diagnose blockage in heart muscles within a finite amount of time in the coronary artery system. As a result, quick recognition of control system performance is essential, and some emergency medicine consumption should be implemented in a certain time frame to prevent the degradation in oxygen delivery to the heart. Despite its benefits, finite-time boundedness analysis has become an important and useful method in the stabilization of a variety of real-world situations [18, 19, 20]. Recently, in [21], finite time synchronization of CACS with actuator faults has been investigated.

Motivated by the above facts, in this paper, we took an attempt to synchronize the diseased system with healthy system with the help of event-triggered reliable control technique. Some sufficient conditions which ensures the synchronization criteria has been derived in terms of LMI. Finally the derived results are verified with the numerical example.

Problem formulation and Preliminaries

The mathematical modeling of the coronary artery system is given by

(1)
$$\begin{cases} \dot{\delta}_1 = -\kappa_1\delta_1 - \kappa_2\delta_2 \\ \dot{\delta}_2 = -(\kappa_1+1)\eta\delta_1 - (\kappa_2+1)\eta\delta_2 + \eta{\delta_1}^3 + E\cos\nu t \end{cases}$$

where $\delta_1(t)$ and $\delta_2(t)$ denotes the inner diameter and pressure of the coronary artery vessel. κ_1, κ_2, η and E denotes the periodically perturbed parameters.

One can remodel the above equation as

$$\dot{\delta}_h(t) = G\delta_h(t) + H\phi(\delta_h(t)) + f(t) \quad (2)$$

where $\delta_h(t) = [\delta_{h1}(t)\ \delta_{h2}(t)]$ denotes the state vector of the healthy coronary artery system. G and H are constant matrices in terms of κ_1, κ_2, η and E. $\phi(\delta_h(t))$ and $f(t)$ stands for the nonlinear functions.

The diseased coronary artery system can be defined as

(3) $$\dot{\delta}_d(t) = G\delta_d(t) + H\phi(\delta_d(t)) + w(t) + v(t)$$

where $\delta_d(t) = [\delta_{d1}(t)\ \delta_{d2}(t)], \phi(\delta_d(t))$ and $w(t)$ represents the state vector, nonlinear vector functions of the diseased coronary artery system. $v(t)$ denotes the control vector.

Define the error dynamics as $\zeta(t) = \delta_d(t) - \delta_h(t)$. The error system can be written as

(4) $$\dot{\zeta}(t) = G\zeta(t) + H\phi(\delta_d(t), \delta_h(t)) + w(t) + v(t)$$

where $\phi(\delta_d(t), \delta_h(t)) = \delta_d(t) - \delta_h(t)$. In an aim to synchronize the diseased system with the healthy system, the event-triggered controller is designed as

(5) $$v(t) = PM\zeta(t_k)$$

where P is the actuator fault matrix and M is the gain matrix to be determined. The Matrix P can be defined as $P = P_0 + diag\{\omega_1, \omega_2, \cdots, \omega_n\}, |\omega_i \leq p_{i1}, i = 1, 2, \cdots, p|$ where $P_0 = diag\{p_{10}, p_{20}, \cdots, p_{n0}\}, p_{i0} = \frac{\bar{p}_i + \underline{p}_i}{2}, 0 \leq \underline{p}_i \leq p_i \leq \bar{p}_i$. Simialrly as in [[15]], (5) can be written as

(6) $$v(t) = P_i M_i z_i(t) + P_i M_i \zeta_i(t - \sigma_i(t))$$

where $0 \leq \sigma_i(t) \leq \sigma(t)$ and satisfies

(7) $$z_i(t) O_i z_i(t) \leq \nu_i \zeta_i^T(t - \sigma(t)) O_i \zeta_i(t - \sigma(t))$$

From(4) and (7) we will get

(8) $$\begin{aligned}\dot{\zeta}(t) &= G\zeta(t) + H\phi(\delta_d(t), \delta_h(t)) + w(t) \\ &\quad + PMZ(t) + PM\zeta(t - \sigma(t))\end{aligned}$$

Assumption 1: Assume that the disturbance $w(t)$ satisfies $\int_0^{t_f} w^t(s)w(s)\mathrm{d}s < w_f$, where w_f is a positive constant.

Definition 1: [22] The system (8) is finite time bounded if $\sup\{\zeta^T(i)F\zeta(i), \dot{\zeta}^T(i)F\dot{\zeta}(i)\} \leq \alpha_1 \rightarrow \zeta^T(i)F\zeta(i \leq \alpha_2, \forall i \in 1, 2, \cdots, t_f$, where $\alpha_1 < \alpha_2$ is a scalar and F is a symmetric matrix and $t_f \in \mathbb{N}$.

Lemma 1: [23] For any matrix $X \in \mathbb{R}^{n \times m}, X = X^T > 0$ differentiable function υ from $[a, b] \rightarrow \mathbb{R}^n$, the following inequality holds:

(9) $$\int_a^b \dot{\upsilon}^T(s) X \dot{\upsilon} \mathrm{d}s \geq \frac{1}{b-a} \Pi^T \begin{bmatrix} X + \frac{\pi^2}{4}X & -X + \frac{\pi^2}{4}X & -\frac{\pi^2}{2}X \\ * & X + \frac{\pi^2}{4}X & -\frac{\pi^2}{2}X \\ * & * & \pi^2 X \end{bmatrix} \Pi$$

where $\Pi = \begin{bmatrix} \upsilon^T(b) & \upsilon^T(a) & \int_a^b \frac{1}{b-a}\upsilon^T(s)\mathrm{d}s \end{bmatrix}$.

Main Results

In this section, our aim is to design event triggered controller for synchronizing diseased system with healthy system.

Theorem 1: If there exists positive definite matrices, $S, \bar{S}_i$, positive scalars and appropriate dimensioned matrices M with positive scalars σ, and symmetric matrix F such that the following LMI holds:

(10) $$\Psi < 0$$

where

$$\Psi(1,1) = 2S_1G + S_2 + S_3 + \sigma^2 G^T S_4 G - (X + \frac{\pi^2}{4}X) + S_1 H H^T S_1^T + K^2 I + H^T K^2 \sigma^2 S_4 H + \sigma^2 H^T K S_4 G + \sigma^2 P M^T S_4 H K,$$

$$\Psi_{1,2} = 2S_1 PM + G^T S_4 PM + (X - \frac{\pi^2}{4}X), \Psi_{1,5} = \frac{\pi^2}{2}S_3,$$

$$\Psi_{1,6} = \sigma^2 G^T S_4, \Psi_{1,7} = \sigma^2 G^T S_4 PM$$

$$\Psi_{2,2} = -X - \frac{\pi^2}{2}X - S_2, \Psi_{2,3} = X - \frac{\pi^2}{4}X, \Psi_{2,4} = \frac{\pi^2}{2}X,$$

$$\Psi_{3,3} = -2X - 2\frac{\pi^2}{4}X + P^T M^T S_4 M P - (1 - \mu)S_3 + \nu O,$$

$$\Psi_{3,4} = \frac{\pi^2}{2}X, \Psi_{3,5} = \frac{\pi^2}{2}X, \Psi_{4,4} = -\pi^2 X, \Psi_{5,5} = -\frac{\pi^2}{2}X,$$

$$\Psi_{5,5} = -\frac{\pi^2}{2}X, \Psi_{3,6} = PM^T S_4, \Psi_{3,7} = P^T M^T S_4 M P,$$

$$\Psi_{6,6} = S_4 - \delta I, \Psi_{6,7} = S_4 PM, \Psi_{7,7} = -O,$$

$$\rho_1 = \rho_{\max}\{S_1\}, \rho_2 = \rho_{\min}\{S_2\}, \rho_3 = \rho_{\min}\{S_3\},$$

$$\rho_4 = \rho_{\min}\{S_4\}, \rho_5 = \rho_{\min}\{S_5\}$$

then the system is finite time stable. Furthermore, the gain matrix is defined as $M = YPS_4^{-1}$.

Proof: Consider the following Lyapunov-krasovkii functional,

(11) $$\zeta(t) = \sum_{i=1}^{4} \zeta_i(t)$$

(12) where

$$\zeta_1(t) = \vartheta^T(t) S_1 \vartheta(t)$$

$$\zeta_2(t) = \int_t^{t-\sigma} \vartheta^T(t) S_2 \vartheta(t) \mathrm{d}s$$

$$\zeta_3(t) = \int_{t-\sigma(t)}^{t} \vartheta^T(t) S_3 \vartheta(t) \mathrm{d}s$$

$$\zeta_4(t) = \sigma \int_{-\sigma}^{0} \int_{t+\theta}^{t} \dot{\vartheta}^T(t) S_4 \dot{\vartheta}(t) \mathrm{d}s$$

By applying the infinitesimal operator $\mathbb{L}$ on both the sides of (11)

(13) $$\begin{aligned}\mathbb{L}\zeta(t) &= 2\vartheta^T(t) S_1 \dot{\vartheta}(t) + \vartheta^T(t) S_2 \vartheta(t) \\ &- \vartheta^T(t-\sigma) S_2 \vartheta(t-\sigma) + \vartheta^T(t) S_3 \vartheta(t) \\ &- (1-\mu)\vartheta^T(t-\sigma(t)) S_3 \vartheta(t-\sigma(t)) + \sigma^2 \dot{\vartheta}^T(t) S_4 \dot{\vartheta}(t) \\ &- \sigma \int_{t-\sigma}^{t} \dot{\vartheta}^T(s) S_4 \dot{\vartheta}(s) \mathrm{d}s\end{aligned}$$

The last term in the above equation (13) can be written as

(14) $$\begin{aligned}-\int_{t-\sigma}^{t} \dot{\vartheta}^T(s) S_4 \dot{\vartheta}(s) \mathrm{d}s &= -\int_{t-\sigma}^{t-\sigma(t)} \dot{\vartheta}^T(s) S_4 \dot{\vartheta}(s) \mathrm{d}s \\ &\quad - \int_{t-\sigma(t)}^{t} \dot{\vartheta}^T(s) S_4 \dot{\vartheta}(s) \mathrm{d}s\end{aligned}$$

By making use of lemma 1,

$$\int_{t-\sigma}^{t-\sigma(t)} \dot{\vartheta}^T(s)S_4\dot{\vartheta}(s)\mathrm{d}s \le \begin{bmatrix} \vartheta(t-\sigma(t) \\ \vartheta(t-\sigma) \\ \frac{1}{\sigma}\int_{t-\sigma}^{t-\sigma(t)}\vartheta(s)\mathrm{d}s) \end{bmatrix}^T \times X_1 \begin{bmatrix} \vartheta(t-\sigma(t) \\ \vartheta(t-\sigma) \\ \frac{1}{\sigma}\int_{t-\sigma}^{t-\sigma(t)}\vartheta(s)\mathrm{d}s) \end{bmatrix} \tag{15}$$

and

$$\int_{t-\sigma(t)}^{t} \dot{\vartheta}^T(s)S_4\dot{\vartheta}(s)\mathrm{d}s \le \begin{bmatrix} \vartheta(t) \\ \vartheta(t-\sigma(t)) \\ \frac{1}{\sigma}\int_{t-\sigma(t)}^{t}\vartheta(s)\mathrm{d}s) \end{bmatrix}^T \times X_1 \begin{bmatrix} \vartheta(t) \\ \vartheta(t-\sigma(t)) \\ \frac{1}{\sigma}\int_{t-\sigma(t)}^{t}\vartheta(s)\mathrm{d}s) \end{bmatrix} \tag{16}$$

where

$$X_1 = \begin{bmatrix} X+\frac{\pi^2}{4}X & -X+\frac{\pi^2}{4}X & -\frac{\pi^2}{2}X \\ * & X+\frac{\pi^2}{4}X & -\frac{\pi^2}{2}X \\ * & * & \pi^2 X \end{bmatrix}$$

By utilizing $\alpha_1^T\alpha_2 + \alpha_2^T\alpha_1 \le \alpha_1^T\alpha_1 + \alpha_2^T\alpha_2$, the nonlinear term can be written as

$$\begin{aligned} 2\vartheta^T(t)S_1\mathfrak{T}\phi(\delta_d(t),\delta_h(t)) &\le \vartheta^T(t)S_1\mathfrak{T}\mathfrak{T}^T S_1^T\vartheta(t) \\ &+ \phi^T(\delta_d(t),\delta_h(t))\phi(\delta_d(t),\delta_h(t)) \\ &\le \vartheta^T(t)[S_1\mathfrak{T}\mathfrak{T}^T S_1^T + K^2 I]\vartheta(t) \end{aligned} \tag{17}$$

where K denotes the Lipschitz constant. By substituting (8) in (13), we will get

$$\begin{aligned} &\sigma^2\dot{\vartheta}^T(t)S_4\dot{\vartheta}(t) = \sigma^2[G^T\vartheta^T(t) + H^T\phi^T(\delta_d(t),\delta_h(t)) \\ &+ P^T M^T z^T(t) + P^T M^T\vartheta^T(t-\sigma(t))]S_4[G\zeta(t) \\ &+ H\phi(\delta_d(t),\delta_h(t)) + w(t) + PMz(t) + PM\zeta^T(t-\sigma(t))] \end{aligned} \tag{18}$$

By making use of (13)-(18), one can get,

$$\mathbb{L}\zeta(t) + \lambda\zeta(t) - w^T(t)\lambda w(t) < \chi^T(t)\Psi\chi(t) \tag{19}$$

where $\Psi(t)$ is defined as in the statement of Theorem 1 and $\chi(t) = [\zeta^T(t)\ \zeta^T(t-\sigma)\ \zeta^T(t-\sigma(t))\ \frac{1}{\sigma}\int\limits_{t-\sigma}^{t-\sigma(t)}\zeta(s)ds\ \frac{1}{\sigma}\int\limits_{t-\sigma(t)}^{t}\zeta(s)ds\ w(t)\ z(t)]$.
From (10), it is obvious that $\Psi < 0$. This implies

$$\mathbb{L}\zeta(t) + \lambda\zeta(t) < w^T(t)\lambda w(t)$$

By integrating from 0 to t_f, we have

$$\zeta(t) < e^{\lambda t_f}\zeta(0) + w_f[e^{\lambda t_f} - 1] \tag{20}$$

For any symmetric matrix F, consider $\tilde{S}_i = F^{-1/2}S_iF^{-1/2}$. From (11), we have

$$\begin{aligned} \zeta(t) \ge \vartheta^T(t)S_1\vartheta(t) &\ge \rho_{\min}\{\tilde{S}_1\}\vartheta^T(t)F\vartheta(t) \\ &= \rho_1\vartheta^T(t)F\vartheta(t) \end{aligned} \tag{21}$$

$$\begin{aligned} &\zeta(0) = \vartheta^T(0)S_1\vartheta(0) + \int_{-\sigma}^{0}\vartheta^T(s)S_2\vartheta(s)\mathrm{d}s \\ &+ \int_{-\sigma(t)}^{0}\vartheta^T(s)S_3\vartheta(s)\mathrm{d}s + \sigma\int_{-\sigma}^{0}\int_{\theta}^{0}\dot{\vartheta}^T(s)S_4\dot{\vartheta}(s)\mathrm{d}s\mathrm{d}u \\ &< [\rho_2 + \sigma(\rho_3+\rho_4) + \frac{\sigma^2}{2}\rho_5]\varphi_1 \end{aligned} \tag{22}$$

Now by using (20) to (22) we get

$$\begin{aligned} \zeta^T(t)F\zeta(t) &< \frac{1}{\rho_1}e^{-\lambda t_f}[\rho_2 + \sigma(\rho_3+\rho_4) \\ &+ \frac{\sigma^2}{2}\rho_5]\varphi_1 - w_f[e^{\lambda t_f} - 1] \end{aligned} \tag{23}$$

From the Lyapunov stability theory and Definition 1, the error system is finite time bounded with the help of event-triggered reliable control. This completes the proof.

Numerical Simulations

In this section, numerical example is provided to check the theoretical results. Consider the coronary artery system with following parameters:

$$G = \begin{bmatrix} -0.15 & 1.7 \\ 0.575 & -0.35 \end{bmatrix}, H = \begin{bmatrix} 0 & 0 \\ 0 & -0.5 \end{bmatrix},$$

$$L = \begin{bmatrix} 0 & 0 \\ 0 & 0.36 \end{bmatrix}, \delta_d = \begin{bmatrix} -1 \\ -1.5 \end{bmatrix}, \delta_h = \begin{bmatrix} 0.5 \\ 0 \end{bmatrix}.$$

Assume $\rho_1 = 0.3, \rho_2 = 7, \lambda = 2$ The actuator fault matrix M is assumed as 0.5. By solving the LMIs obtained from theorem 1, the controller gain matrices and triggering matrices are given by

$$M = \begin{bmatrix} -1.0019 & 0.0015 \\ -2.0013 & -0.0016 \end{bmatrix},$$

$$O = \begin{bmatrix} 0.0310 & -0.0052 \\ -0.0052 & 0.0156 \end{bmatrix}$$

Fig 1 and fig 2 represents the state trajectories of healthy and diseased CACS. By applying the control gain matrices in the diseased CACS, the state trajectories of the error response in given in figure 3.

Conclusion

In this work, event-triggered reliable synchronization problem of chaotic coronary artery system was examined. The designed event triggered reliable controller is intended to restrict an abnormal cardiac rhythm, which is required to deliver nourishment and oxygen to the heart at all times of the day and night, despite unpredictable factors such as medicine use, emotional changes, and so on. By assuming appropriate Lyapunov Krasovskii functional, some criteria which ensure the finite time synchronization of addressed system is derived in the form LMI. For validate the theoretical results numerical simulations are performed.

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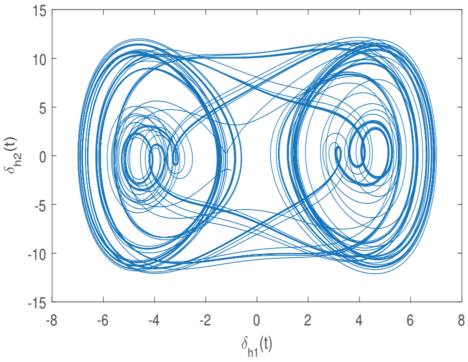

Fig. 1. State trajectories of Healthy system

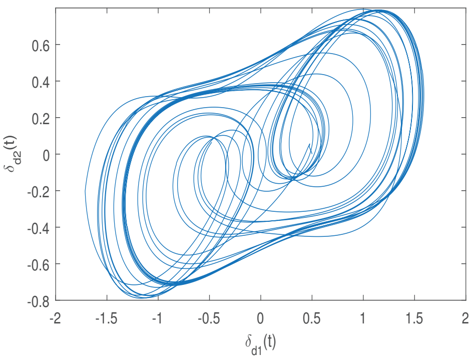

Fig. 2. State trajectories of Diseased system

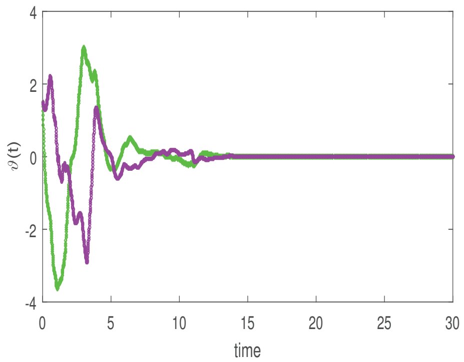

Fig. 3. State trajectories of error system

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