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Different types of nonlinear sliding mode technique for nonlinear uncertain type 1 diabetes model

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Abstract

In this paper, the robust controller is designed based on different types of sliding mode techniques for the nonlinear model of Bergman insulin-glucose regulation of type 1 diabetes. It is assumed that the nonlinear model includes unknown uncertainties. The convergence of patient person states to the healthy guy ones is the main purpose of the presented designing procedures. The stability of the closed-loop system, the robustness of suggested schemes, and the convergence of tracking error to zero in finite time are the main advantages of the suggested method. The reduction of chattering phenomena is guaranteed in this approach. The proposed methods depict the promising performance of the derived controllers in the injected rate of insulin in diabetes diseases. The simulation results illustrate the promising performance of the planned policy. Also, the sliding mode techniques are compared with the others to show the best-proposed design.

Keywords: Super-Twisting, Fixed-Time, Sliding Mode Control, Bergman Insulin-Glucose Regulation, Diabetes.
2020 MSC: 70K75, 93C10

1 Introduction

Diabetes is one of the common chronic diseases in the world. The World Health Organization (WHO) guesses that societies with diabetes will touch 5.4% by 2030 [8]. This metabolic disease is caused by insulin deficiency in the body [21]. In other words, this is a metabolic disease which the pancreas can not adjust the blood glucose stages within normal range (70-150 mg/dL) [1]. High blood glucose has several side effects such as blindness, kidney failure, neurological damage and heart attack [8].

There are two types of diabetes: type I and type II. In type I diabetes, the insulin producing β-cells in the pancreas is attacked by the immune system [1]. Thus, these patients need the continuous injection of external insulin [22]. But type II diabetes is accompanied by the reduction in insulin efficiency to promote transport of glucose into the cells and does not require insulin injections [10].

Diabetes diagnosis is based on a fasting blood glucose concentration above the normal level [9]. So, a diabetic person should be perform the procedures of blood glucose regulation manually. But if a system have existed that automatically monitors and controls blood glucose levels, the diabetic patients can better operate their daily activities [21]. So, in 1974, the initial work in the first generation of control approaches was carried out independently by

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Albisseret and Pfeifferet [18]. This research led to the development of the glucose controlled insulin infusion system (GCIIS).

In [9], George Eisenbarth developed a model for the pathogenesis of type 1 diabetes. In [15], a proportional–integral–derivative (PID) controller based on BP neural networks is applied to condense the time of blood glucose reduction. The robust PID is investigated for regulation of glucose level in type 1 diabetes in [12]. Also, the digital PID controller in [23], and the switching PID controller in [20] are all developed in this approach. In [16], an improved PID strategy is deliberated for blood glucose control, too. It should be noted that there are another control algorithms to close the control loop such as H_∞ control [19].

Also, a model-free based controller such as fuzzy systems is designated to regulate insulin in [24]. For example, in [17], the PID fuzzy controller based on PSO algorithm is designed in order to control the glucose concentration. Another non-linear control algorithms are sliding mode control (SMC) that is handled in [10]. SMC is a nonlinear variable structure control (VSC) method which is composed of two steps. the first step is the choice of the switching surface that the system reaches the switching surface with using the suitable control law. The next step , the system was should keeped on the defined surface [1]. Also, this method is robust against external disturbances and uncertainties[14].

[8] deals with the higher order sliding mode strategies for regulation of the blood glucose in type 1 diabetic patients. In [21], a higher-order sliding mode control back-stepping sliding mode control is designed for this structure, too. Also, [3] studied the super twisting control approach and [1] is investigated the internal model sliding mode control for the glucose regulation in type 1 diabetic patients.

It should be noted that the model used is important in the strategy of glucose regulation. The linear models is developed by Bolie [5] and Ackerman et al [2]. But they are simple and cannot tackle with the control challenges. Regarding nonlinear behaviour of the glucose-insulin dynamics, the different models are suggested such as physiological models that are used by Sorensen [20], Hovorka et al [11] , Dalla Man et al[7] and Lehmann [13]. Also, the mathematical models that are studied by Cobelli and Mari [6] and Bergman et al [4].

Compare to the other researches consentrate on either the simple model or the infinite time controller, this paper focuses on the supertwisting fixed time sliding mode controller for nonlinear model of diabetes in presence of model uncertainties. The following are the merits of the proposed scheme.
1- Finite time convergence of the tracking error to zero
2- Reduction of the chattering phenomena
3- Robustness against uncertainties

Section I presents the problem statement which introduces the model. The controller design explains in Section II. Section III states the simulation results and finally, this paper ends with conclusion in section IV.

2 Problem Formulation

There are many schemes for diabetes modeling [5]. Dr. Richard Bergman was one of them. He is developed the so-called 'Minimal Model'. The Bergman minimal model, answers dynamically to the uncontrolled blood glucose concentration of insulin injections. Minimizing the parameters number and the interaction between concentration of the glucose and insulin are from the advantages of this model [21]. The Bergman nonlinear model is as follows [21]:

$$\begin{aligned}
&\dot{G}_p(t) = -p_1(G_p(t) - G_b) - X_p(t)G_p(t) + D(t)\\
&\dot{X}_p(t) = -p_2X_p(t) + p_3(I_p(t) - I_b)\\
&\dot{I}_p(t) = -n^*(I(t) - I_b) + \gamma(G_p(t) - H)_{t^+} + F_{un} + u(t)
\end{aligned} \tag{2.1}$$

where $G_p(t)$ is the concentration of the plasma glucose in $\frac{mmol}{L}$ or $\frac{mg}{dL}$, $I_p(t)$ is the concentration of the plasma insulin in $\frac{mU}{L}$, $X_p(t)$ is proportional to the concentration of the insulin in the remote compartment in $\frac{mU}{L}$ and $u(t)$ is injected rate of insulin. G_b and I_b are respectively the basal pre-injection level of glucose and the basal pre-injection level of insulin. Also, p_1 is the insulin independent rate constant of glucose uptake in muscles and liver ($\frac{1}{min}$), p_2 is the rate for reduction in the ability of the tissue glucose uptake ($\frac{1}{min}$), p_3 is the dependent increase of the insulin in glucose uptake ability in tissue per unit of insulin concentration above the basal level, n^* is the decay rate of the first-order for insulin in blood ($\frac{1}{min}$), H is the threshold value of glucose above which the pancreatic β cells release insulin , γ is the rate of the pancreatic β cells release of insulin after the glucose injection with glucose concentration above the threshold[21].$D(t)$ shows the rate that glucose absorbed to the blood from the intestine after ingestion of food.

Diabetic patients do not have insulin monitoring system, so this glucose uptake is known as a disturbance. This disturbance can be modeled by(2.2)

$$D(t) = A\exp(-Bt) \tag{2.2}$$

where t is as time in($minutes$)and $D(t)$ is is as disturbance in ($mg\ /dl\ /min$).

Also, the dynamic of the healthy guy can be concluded from the above model.

$$\begin{array}{l} \dot{G}(t) = -p_1^{'}(G(t) - G_b^{'}) - X(t)G(t) + D(t) \\ \dot{X}(t) = -p_2^{'}X(t) + p_3^{'}(I_p\,(t) - I_b^{'}) \\ \dot{I}(t) = -n^*\,(I\,(t) - I_b^{'}) + \gamma(G(t) - H^{'})_{t^+} \end{array} \tag{2.3}$$

where $G(t)$ is the concentration of the plasma glucose in $\frac{mmol}{L}$ or $\frac{mg}{dL}$ in the healthy human , $I(t)$ is the concentration of the plasma insulin in $\frac{mU}{L}$ for the healthy human and $X(t)$ is proportional concentration of the insulin in the remote compartment in $\frac{mU}{L}$ for the healthy human.

The aim of this paper is the convergence of $I(t)$ to $I_p(t)$. $I(t)$ is the state of the healthy model and $I_p(t)$ is the state of the patient one. So, we define error as(2.4):

$$e(t) = I_p(t) - I(t) \tag{2.4}$$

The following lemma will be used in next section.

lemma 1[29] Consider the following differential inequality:

$$\begin{cases} \dot{x}(t) \le -\alpha sign(x(t))|x(t)|^m - \beta sign(x(t))|x(t)|^n \\ x(0) = x_0 \end{cases} \tag{2.5}$$

where α, β, m and n are all real constant that satisfy $\alpha > 0, \beta > 0, m > 1$ and $0 < n < 1$. The state variable $x(t)$ will converge to the origin in a fixed time upper bound by T_{max} so that the following inequality is hold.

$$\lim_{x_0 \to \infty} (T(x_0)) \le T_{\max} \tag{2.6}$$

T_{max} is definded as follows, too.

$$T_{\max} = \frac{1}{\alpha(m-1)} + \frac{1}{\beta(1-n)} \tag{2.7}$$

3 Controller Design

Due to the external uncertainty, the sliding method is used to design the control input. So, in this paper, several sliding mode techniques are designed to make a comparison between them and select the best method.

To design of sliding mode control in the simple mode, the input is considered as (3.1)

$$\begin{array}{l} u(t) = A_1 I_p(t) + A_2 I(t) + A_3 G(t) + A_4 G_p(t) + A_5 I_b(t) - \\ A_6 - k\,sign(S) \end{array} \tag{3.1}$$

where A_1 , A_2, A_3, A_4, A_5, A_6 are the positive constant values and k is positive definite matrix.

Theorem 1: Consider reconfigured closed-loop system mentioned in the equation (2.1) with controller input as mentioned in equation (3.1). The proposed controller makes the dynamic of the error derived in (2.4), uniformly ultimately bounded and besides all the signals involved in a closed loop system are entirely bounded.

proof: First, the sliding surface is considered as follows.

$$S = e(t) = I_p(t) - I(t) \tag{3.2}$$

The time derivative of the equation(3.2) is as follows, too.

$$\dot{S} = \dot{I}_p(t) - \dot{I}(t) \tag{3.3}$$

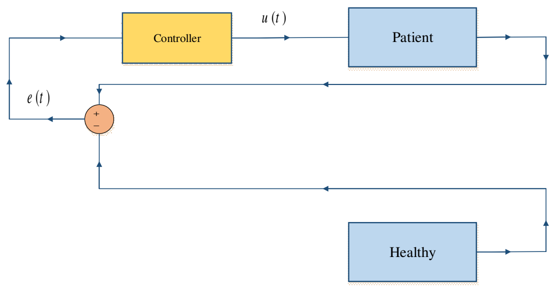

Figure 1: The block diagram designated sliding mode controller.

By using (2.1) and (2.3), we have:

$$\dot{S} = -A_1 I_p(t) - A_2 I(t) - A_3 G(t) - A_4 G_p(t) - A_5 I_b(t) + A_6 - F_{un} - u(t) \tag{3.4}$$

The below Lyapunov function is candidate to investigate the stability of this system.

$$V(t) = \frac{1}{2} S^2 \tag{3.5}$$

The time derivative of Lyapunov function is as:

$$\dot{V}(t) = S\dot{S} \tag{3.6}$$

By equations (3.1) and (3.4), the equation (3.7) is obtained below.

$$\dot{V}(t) < 0 \tag{3.7}$$

Therefore, the time derivative of the Lyapunov function is negative. This implies the uniformly ultimate boundedness of the error. Furthermore, all the signals involved in the closed loop system are all bounded. So, this proof completes.

The figure 1 shows the structure of the designated sliding mode controller.

The input controller for integrator sliding mode control is considered as (3.8)

$$u(t) = A_1 I_p(t) + A_2 I(t) + A_3 G(t) + A_4 G_p(t) + A_5 I_b(t) - A_6 - k\, sign(S) \tag{3.8}$$

where A_1 , A_2, A_3, A_4, A_5, A_6 are the positive constant values and k is positive definite matrix.

Theorem 2: Consider reconfigured closed-loop system mentioned in the equation (2.1) with controller input in the equation (3.8). The dynamic of the error derived in (2.4), is uniformly ultimately bounded with using this input controller. Also, all the signals of the closed loop system are bounded.

proof: The sliding surface is considered as follows.

$$S = e(t) + \alpha \int e(t) \tag{3.9}$$

where $\alpha > 0$.

The time derivative of equation(3.9) is as (3.10).

$$\dot{S} = \dot{I}_p(t) - \dot{I}(t) + \alpha(I_p(t) - I(t)) \tag{3.10}$$

By equations (2.1) and (2.3), we have:

$$\dot{S} = -A_1 I_p(t) - A_2 I(t) - A_3 G(t) - A_4 G_p(t) - A_5 I_b(t) + A_6 - F_{un} - u(t) \tag{3.11}$$

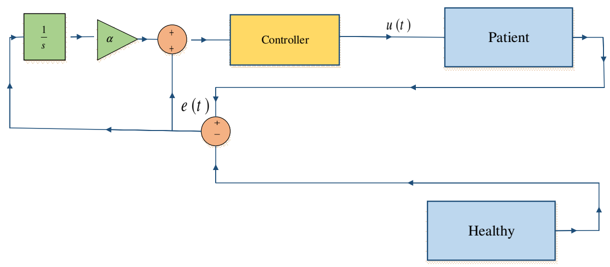

Figure 2: The block diagram integrator sliding mode controller.

The Lyapunov function to investigate stability of this system is candidate as follow.

$$V(t) = \frac{1}{2}S^2 \tag{3.12}$$

The time derivative of euation (3.12) is as below.

$$\dot{V}(t) = S\dot{S} \tag{3.13}$$

By equations (3.8) and (3.11), the equation (3.14) is obtained below.

$$\dot{V}(t) < 0 \tag{3.14}$$

The time derivative of the Lyapunov function is negative definite. So, the closed loop system leads to uniformly ultimatly bounded and all the signals involved in the system are bounded. The figure 2 shows the structure of the designated controller.

In the third method, the second- order sliding mode control is studied in this section. Consequently, the input controller is considered as follows:

$$u(t) = \frac{\hat{u}(t) + \dot{u}(t)}{s - A_3} \tag{3.15}$$

where $\dot{u}(t)$ is the time derivative of the input.A_3 is the positive constant and $\hat{u}(t)$ is as follows:

$$\begin{aligned}&\hat{u}(t) = -A_1 I_p(t) + A_2 + A_4 I(t) - A_5 G(t) - A_6 G(t)X(t)- \\ &\alpha sign(S) - \beta sign(\dot{S})\end{aligned} \tag{3.16}$$

where A_1 , A_2, A_3, A_4, A_5, A_6 are the positive constants and $\alpha, \beta > 0$.

Theorem 3: Consider reconfigured closed-loop system mentioned in the equation (2.1) with controller input in the equation (3.15).This controller caused that the error in equation (2.4) be uniformly ultimately bounded and all the signals of the closed loop system are wholly bounded.

proof: The sliding surface in the second order sliding mode control is considered as (3.17).

$$S = e(t) \tag{3.17}$$

Although, S and $\dot{S}$ must be converge to zero.

The time derivative of equation(3.17) is as (3.18).

$$\dot{S} = \dot{I}_p(t) - \dot{I}(t) \tag{3.18}$$

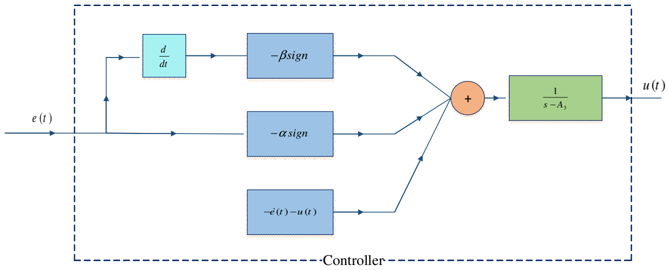

Figure 3: The block diagram second order sliding mode controller.

By quations (2.1) and (2.3), the (3.19) is obtained.

$$\begin{aligned}&\dot{S} = -A_1 I_p(t) - A_2 I(t) - A_3 G(t) - A_4 G_p(t) - A_5 I_b(t) + \\ &A_6 - F_{un} - u(t)\end{aligned} \tag{3.19}$$

Also, the time derivative of equation(3.19) is as (3.20).

$$\ddot{S} = -A'_1 \dot{I}_p(t) + A'_2 \dot{I}(t) - A'_3 G(t) + \dot{u}(t) \tag{3.20}$$

where $A_1^{'}$, $A_2^{'}$, $A_3^{'}$ are the positive constants.

Using equations (3.15) and (3.16), we have:

$$\ddot{S} = -\alpha sign(S) - \beta sign(\dot{S}) \tag{3.21}$$

To achieve the second-order sliding mode, $S = \varepsilon$, $\dot{S} = \delta$ is definded. Then, the equation (3.22) is obtained from the (3.21).

$$\begin{cases} \dot{S} = \delta \\ \dot{\delta} = -\alpha sign(\varepsilon) - \beta sign(\delta) \end{cases} \tag{3.22}$$

Finally, the Lyapunov function is candidate to investigate the stability of this system.

$$V(t) = \int_0^{\varepsilon} \alpha sign(\tau) d\tau + \frac{1}{2}\delta^2 \tag{3.23}$$

The time derivative of this Lyapunov function is as below.

$$\dot{V}(t) = \dot{\varepsilon}\alpha sign(\varepsilon) + \delta\dot{\delta} \tag{3.24}$$

The equation (3.25) is obtained by using the (3.22).

$$\dot{V}(t) = \delta\alpha sign(\varepsilon) + \delta(-\alpha sign(\varepsilon) - \beta sign(\delta)) \leq 0 \tag{3.25}$$

According to Lassalle theory, the equation(3.26) is resulted.

$$\dot{V}(t) = 0 \to \varepsilon, \delta = 0 \tag{3.26}$$

So, the proof is complete.

The figure 3 shows the structure of the designed controller, too.

In the next step, the super twisting sliding mode control input is as (34)

$$\begin{aligned}&u(t) = A_1 I_p(t) + A_2 I(t) + A_3 G(t) - A_4 - \alpha |S|^{\rho} sign(S) \\ &-\beta \int sign(S) dt\end{aligned} \tag{3.27}$$

where A_1 , A_2, A_3, A_4 are the positive constants, α, β are positive values and $0 < \rho < 1$.

Theorem 4: Consider reconfigured closed-loop system mentioned in the equation (2.1). The proposed control input as in equation (3.27) makes this system uniformly ultimatly bounded and all the signals in the closed loop system are entirely bounded.

proof: The sliding surface is considered as follows.

$$S = e(t) = I_p(t) - I(t) \tag{3.28}$$

The time derivative of the above equation is as (3.29).

$$\dot{S} = \dot{I}_p(t) - \dot{I}(t) \tag{3.29}$$

Using (2.1) and (2.3), we have:

$$\begin{aligned} &\dot{S} = -A_1 I_p(t) - A_2 I(t) - A_3 G(t) - A_4 G_p(t) - A_5 I_b(t) + \\ &A_6 - F_{un} - u(t) \end{aligned} \tag{3.30}$$

where A_1 , A_2, A_3, A_4, A_5, A_6 are the positive constants.

Then, $S = \xi\,, \delta = -\beta \int sign(S)dt$ are definded and using equation (3.27), the equation (3.30) can be written as (3.31).

$$\begin{cases} \dot{\xi}(t) = \delta(t) - \alpha|\xi|^{\rho} sign(\xi) \\ \dot{\delta} = -\beta sign(\xi) \end{cases} \tag{3.31}$$

To investigate stability of the closed loop system, the Lyapunov function is candidate as follow.

$$V(t) = \beta \int_0^{\xi} \alpha sign(\tau)d\tau + \frac{1}{2}\delta^2(t) \tag{3.32}$$

where $\alpha, \beta > 0$.

The time derivative of this Lyapunov function is as below.

$$\dot{V}(t) = \beta\dot{\xi}(t)sign(\xi) + \delta(t)\dot{\delta}(t) \tag{3.33}$$

The equation (3.34) is obtained by means of the (3.31).

$$\begin{aligned} &\dot{V}(t) = -\beta[\delta(t) - \alpha|\xi|^{\rho} sign(\xi)]sign(\xi) + \\ &\delta(t)(-\beta sign(\xi)) \leq 0 \end{aligned} \tag{3.34}$$

According to Lassalle theory, the equation(3.35) is resulted.

$$\dot{V}(t) = 0 \rightarrow (\xi, \delta) = (0, 0) \tag{3.35}$$

So, proof is complete and all the signals in system are uniformly ultimatly bounded

The figure 4 shows the structure of the designed controller.

The fixed-time sliding mode control input is suggested as follows:

$$\begin{aligned} &u(t) = A_1 I_p(t) + A_2 I(t) + A_3 G(t) + A_4 G_p(t) + A_5 I_b(t) - \\ &A_6 + \alpha sign(e)|e|^m + \beta sign(e)|e|^n + \alpha sign(S)|S|^m + \\ &\beta sign(S)|S|^n \end{aligned} \tag{3.36}$$

where A_1 , A_2, A_3, A_4, A_5, A_6 are the positive constants and $\alpha, \beta > 0$, $m > 1$ and $0 < n < 1$.

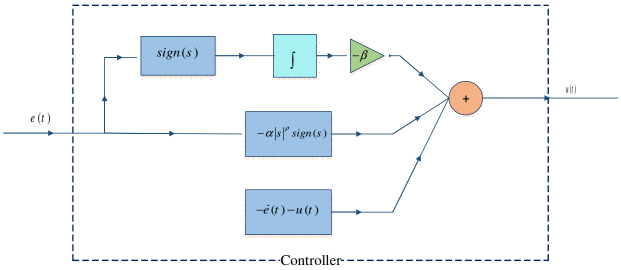

Figure 4: The block diagram super twisting sliding mode controller.

Theorem 5: Consider reconfigured closed-loop system mentioned in the equation (2.1) with controller input in the equation (3.36). The proposed fixed-time sliding mode control input in equation(3.36) makes this system uniformly ultimatly bounded and the error in (2.4), is uniformly ultimately bounded, too.

proof: In this method, the sliding surface is considered as (3.37).

$$S = e(t) + \alpha \int_0^t sign(e)|e|^m + \beta \int_0^t sign(e)|e|^n \tag{3.37}$$

The time derivative of equation(3.37) is as follows.

$$\dot{S} = \dot{e}(t) + \alpha sign(e)|e|^m + \beta sign(e)|e|^n \tag{3.38}$$

The equation(3.39) is obtained via equations (2.1) and (2.3).

$$\begin{aligned} \dot{S} = -A_1 I_p(t) - A_2 I(t) - A_3 G(t) - A_4 G_p(t) - A_5 I_b(t) + \\ A_6 - F_{un} - u(t) + \alpha sign(e)|e|^m + \beta sign(e)|e|^n \end{aligned} \tag{3.39}$$

Then the Lyapunov function is candidate to investigate the stability of this system.

$$V(t) = \frac{1}{2} S^2 \tag{3.40}$$

The time derivative of this Lyapunov function is as below.

$$\dot{V}(t) = S(t)\dot{S}(t) \tag{3.41}$$

Finally by means of the equations (3.37) and (3.39), The equation (3.42) is obtained.

$$\dot{V}(t) = S(t)(-\alpha sign(S)|S|^m - \beta sign(S)|S|^n) \tag{3.42}$$

As can be seen, the Lemma 1 has been established and it can be concluded that the error is uniformly ultimate bounded. Furthermore, all the signals involved in the closed loop system are bounded and this theory is proved.

The figure 5 shows the structure of the controller structure.

4 Simulation result

In this paper, the system dynamic is considered based on the Bergman model. The specification of Bergman parameters is available on table 1 [21].

Figure 6 shows the output of the patient model and the healthy one via the sliding mode controller (SMC) with $k = 2$. As shown in Figure 6, the patient model tracks the healthy one and consequently, e achieves to zero.

Figure 7 shows the outputs of healthy and patient model by way of the integraller sliding mode controller (ISMC) by $\alpha = 5$.

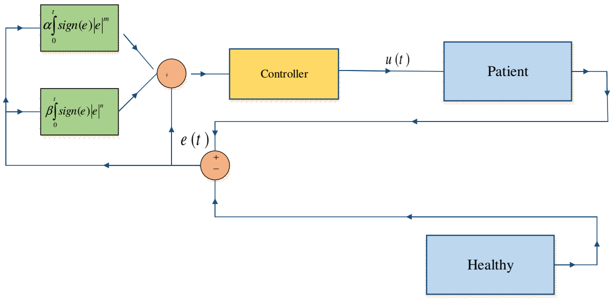

Figure 5: The block fixed time sliding mode controller.

parameter	healthy	patient
$\rho_1(\rho_1^{'})$	0.0317	0
$\rho_2(\rho_2^{'})$	0.0123	0.0123
$\rho_3(\rho_3^{'})$	$8.2 * 10^{-8}$	$8.2 * 10^{-8}$
γ	$6.5 * 10^{-5}$	0
n^*	0.2659	0.2659
$H(H^{'})$	79.0353	0
$G_b(G_b^{'})$	70	70
$I_b(I_b^{'})$	7	7
G_0	140	140
I_0	20	20

Table 1: The parameters of the Bergman model

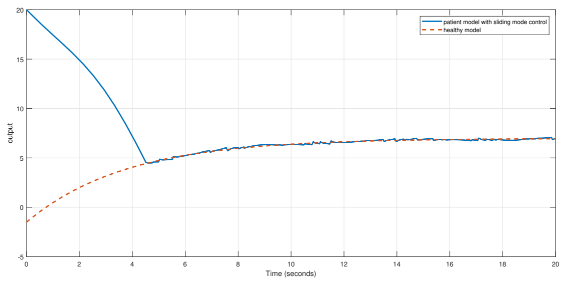

Figure 6: The output of the patient model and the healthy one via SMC

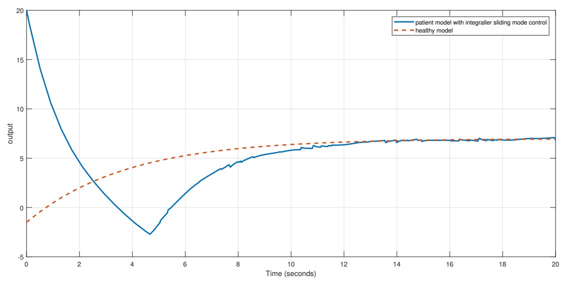

Figure 7: The output of the patient model and the healthy model with ISMC.

Also, Figure 8 shows the outputs of patient and healthy model by the second order sliding mode controller (SOSMC) by $\alpha = 4$ and $\beta = 3$.

In this method, the patient system is tracking to the healthy system and subsequently e succeeds to zero.

Figure 9 shows these outputs consuming the super twisting sliding mode controller (STSMC) that $\alpha = 5$ and $\beta = 6$

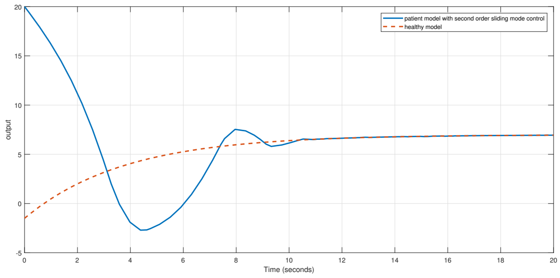

Figure 8: The output of patient and healthy model with SOSMC.

are considered.

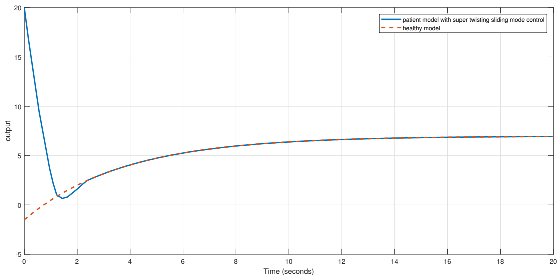

Figure 9: The output of the patient model and the healthy model STSMC.

Also, these results are studied based on the fixed time sliding mode controller (FTSMC) when $\alpha = 10, \beta = 7\,, n = 0.5$ and $m = 1.5$.

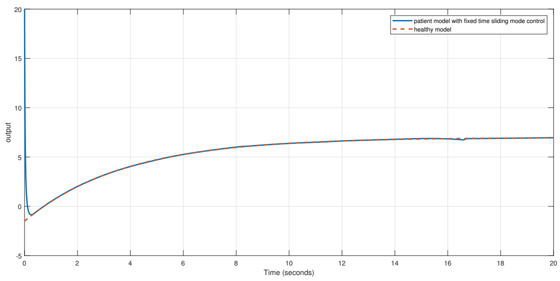

Figure 10: The output of the patient model and the healthy model using FTSMC.

In order to compare the results, the figure11 is displayed all the controller methods.

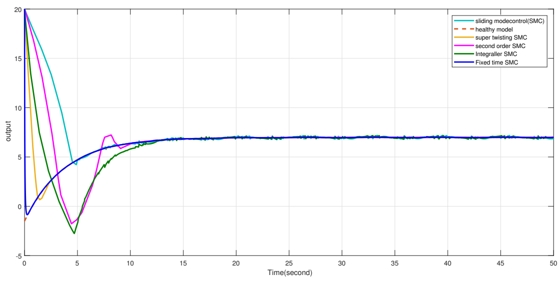

Figure 11: The outputs of patient and healthy model based on the proposed methodologies.

As shown in Figure 11, all of the patient output results well track the healthy one. Among all the outcomes mentioned in this section, the fixed time sliding mode control seem to be the most appropriate decision with much shorter time convergence to zero than the others.

5 Conclusion

This paper deals with a wide calss of sliding mode controller for nonlinear diabets model. A sliding mode controller was designated for a mentioned model. The classic SMC has following drawbacks of the chattering as 1) the controller's accuracy decreases, 2) thermal losses, and 3) the activation of high-frequency nonlinear dynamics. The second-order sliding mode procedure has been suggested to reduce chattering. The differential of the sliding surface in designing procedure is main difficulties of the planned approach. The super twisting SMC has been suggested both to reduce chattering phenomena and to be more applicable, and subsequently it leads to better performance in tracking than the other methodologies. Finally, the fixed time SMC leads to convergence of the tracking error to zero in fixed time as 0.4857s. all the mentioned methodology is applied to the nonlinear Bergman model and the simulation results illustrate the promising performance of the proposed controller design procedures.

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