Super Twisting Control Algorithm for Blood Glucose Regulation in Type 1 Diabetes Patients

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***Abstract*—This is an increasing belief that consequences due to hyperglycemia can be mitigated using a close loop control system. This paper investigates a robust non-linear control approach based on sliding mode control (SMC) algorithm for type 1 diabetes patients. Bergman's minimal model have been used to analyse the behaviour of glucose and insulin dynamics in blood plasma inside human body. Control law based on super twisting SMC algorithm is formulated and simulated. Results demonstrated the performance and effectiveness of the proposed control scheme. Also the proposed control scheme is compared with traditional SMC on the basis of performance parameters in the presence of external disturbances. Results dictate that the proposed control law exhibits robustness and overperforms by demonstrating accurate trajectory tracking with relatively less control efforts and alleviating chattering.**

***Index Terms*—Type 1 diabetes, Bergman minimal model, robust control, traditional SMC, super twisting SMC, external perturbation.**

I. Introduction

In the present era, Diabetes Mellitus (DM) is one of the most common metabolic disorder across the world, whose prevalence has continued to increase drastically. The statistical analysis put forward by World Health Organization (WHO) that diabetes victims increased from 108 millions to 422 millions from 1980 to 2014 [1]. According to a report of International Diabetes Federation, there will be approximately 642 million diabetes patients in 2040, if no reasonable precautions are taken [2]. Due to high prevalence rate across the world, it is anticipated that in future diabetes would be the number seven leading cause of death.

DM is a combination of metabolic disorders characterized by hyperglycemia, which results from abnormal behaviour of insulin secretion, resistive action of insulin, or both. The enormous majority of cases of diabetes are categorized into two broad categories: In type 1 diabetes, which is caused by insufficiency of insulin secretion, the hormones are responsible to control glucose concentration in blood plasma. Whereas, in type 2 diabetes, the body becomes resistant to insulin action and loses the capability to produce insulin. In the present study, type 1 diabetes is under consideration, in which pancreas loses the capability to produce sufficient amount of insulin, due to which the glucose level in blood remains dangerously high for long period of time, resulting in hyperglycaemia. Untreated hyperglycaemia results in chronic issues such as cardiovascular diseases, diseases related with bones, joints and skin and damaging nerves, kidneys and retina etc. [3]. The aforementioned complications stimulate an urge to design a precise controller to maintain optimal glucose concentration in blood plasma of diabetes patients. Owing to the fact, the formulation of accurate control method for achieving basal concentration of glucose in blood plasma of type 1 diabetes patients remained an exciting research area over last few decades.

The linear control methods investigated for regulation of glucose level in type 1 diabetes patients are based on Proportional Integral Derivative (PID) control algorithms [4] i.e. robust PID control approach [5], digital PID controller [6], expert PID controller [7], genetic control algorithm based on PID control strategy [8] and switching based PID control scheme [9]. Other linear control schemes for regulation of glucose concentration are feed forward-feedback control strategy [10], control law based on pole placement technique and controller based on discrete model prediction algorithm [11]. Besides linear control techniques, researchers have also shown keen interest in designing non-linear control laws for regulation of glucose level to obtain the required desired performance. As regulation of glucose concentration in blood plasma is a nonlinear process in nature, thus nonlinear control schemes can provide better performance as compared to linear control method based on linearized model. Reported non-linear control algorithms are based on model predictive control [12], high order sliding mode control [13], fuzzy logic control [14], adaptive gain high order sliding mode control using fuzzy logic [15], recurrent based neural network control [16], fractional order PID control scheme [17], Sliding Mode Control (SMC) based on Backstepping technique [18] and fractional sliding mode controller with adaptive gains [19].

In this article, a non-linear super twisting control algorithm based on SMC approach has been addressed for regulation of glucose concentration in blood plasma of type 1 diabetes patients. Closed loop system stability analysis has been carried out using lapanaov stability theory. To validate the robustness of the proposed control algorithm, the system is exposed to external disturbances.

The paper is categorized into four sections. In Section II, Bergmans minimal model has been formulated. Section III investigates the controller and presents stability analysis of the closed loop system. In section IV, simulation results have been provided with thorough discussion. Finally, the conclusion is presented in section V.

II. MATHEMATICAL MODEL

To develop mathematical model of insulin-glucose dynamics inside human body, various models have been derived and investigated. Among these models, Bergmans minimal model has been chosen for the proposed controller due to its uniqueness as a ‘reference model’ [13]. The model is based on mass balance theory [19]. Table 1 presents nomenclature of various symbols used in this paper. Wherever applicable, values of system parameters are also listed.

TABLE I
NOMENCLATURE

Symbol	Description	Value	Units
G(t)	Actual value of glucose	-	mg/dl
G_b	Basel value of glucose	80	mg/dl
X(t)	Effect of active insulin	-	$1/min$
I(t)	Actual level of insulin	-	U/ml
I_b	Basel level of insulin	7	U/ml
h	Threshold value of glucose	79.0353	mg/dl
n	First order decay rate	0.31	$1/min$
γ	Secretion rate of insulin	0.0039	$\mu U.mg/ml.min^2.dl$

Bergmans minimal model incorporates two major dynamics; glucose and insulin. Glucose dynamics can be expressed by two differential equations given below.

$$\frac{dG(t)}{dt} = -\big(\alpha_1 + X(t)\big)G(t) + \alpha_1 G_b$$
$$\frac{dX(t)}{dt} = -\alpha_2 X(t) + \big(I(t) - I_b\big)\alpha_3$$

where α_1, α_2, α_3 are rates corresponding to insulin independent consumption of glucose in liver and periphery, Decay rate of glucose consumption in tissues, insulin dependent consumption rate of glucose respectively. The circulation of insulin and glucose inside human body is illustrated in Fig. 1. It also demonstrates the effect of active insulin over excess amount of glucose level in blood plasma. External disturbance is shown as glucose dosage.

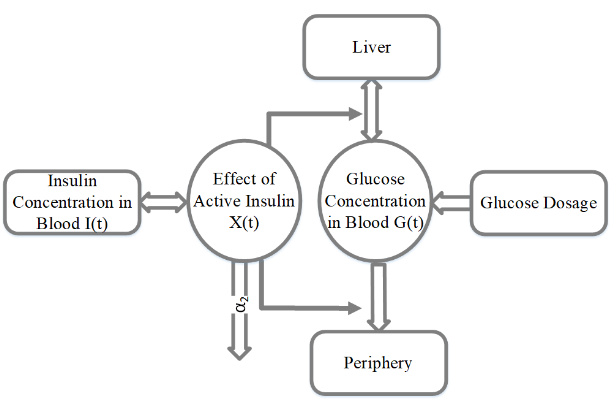

Fig. 1. Block diagram of glucose kinetics.

Insulin dynamics can be expressed as

$$\frac{dI(t)}{dt} = -n\big(I(t) - I_b\big) + \gamma[G(t) - h]^+ t$$

Fig. 2 depicts the dynamical behaviour of insulin concentration inside human body. Whenever glucose concentration exceeds the optimal level, impulse is sent to pancreas to produce insulin, so as to keep the glucose level normal.

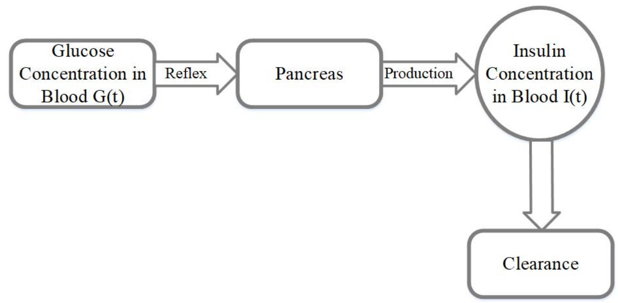

Fig. 2. Model describing insulin kinetics

In state space form, Bergman’s minimal model of insulin-glucose dynamics inside human body can be expressed as;

$$\left.\begin{aligned} \dot{x_1}(t) &= -\big(\alpha_1 + x_2(t)\big)x_1(t) + \alpha_1 G_b \\ \dot{x_2}(t) &= -\alpha_2 x_2(t) + \big(x_3(t) - I_b\big)\alpha_3 \\ \dot{x_3}(t) &= -n\big(x_3(t) - I_b\big) + \gamma[x_1(t) - h]^+ t \end{aligned}\right\} \quad (1)$$

where $x_1(t)$ is the concentration of glucose, $x_2(t)$ represents the effect of active insulin on glucose concentration, while $x_3(t)$ is the concentration of insulin in blood plasma.

III. ROBUST NON-LINEAR CONTROL ALGORITHM BASED ON SMC APPROACH

The block diagram of type 1 diabetes patient along with the proposed controller in closed loop form is given in Fig. 3. Control input is actually the insulin infusion rate, which is further used by insulin pump to inject insulin into diabetes patient.

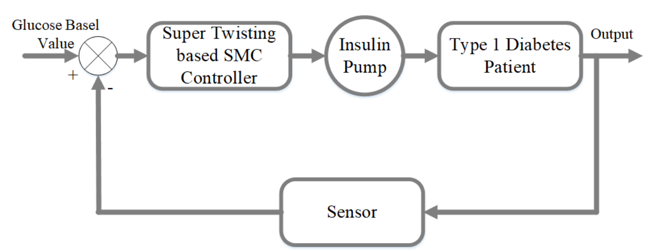

Fig. 3. Block Diagram of type 1 diabetes patient along with the proposed controller

Bergmans minimal model given in (1) can be formulated for type 1 diabetes patient as

$$\left.\begin{aligned} \dot{x_1}(t) &= -\big(\alpha_1 + x_2(t)\big)x_1(t) + \alpha_1 G_b + D(t) \\ \dot{x_2}(t) &= -\alpha_2 x_2(t) + \big(x_3(t) - I_b\big)\alpha_3 \\ \dot{x_3}(t) &= -n\big(x_3(t) - I_b\big) + u(t) \end{aligned}\right\} \quad (2)$$

where $D(t)$ is the external meal disturbance and is introduced in the model to study its effect on glucose concentration in blood plasma i.e $D(t) = Ae^{-Bt}$, $B > 0$. $\gamma[x_1(t) - h]^{+}t$ is considered as zero here since there is no release of insulin by pancreas in type 1 diabetes patients [20]. The control input $u(t)$ shows the infusion rate of insulin in blood plasma.

A. Controller Design

SMC is a robust non-linear control algorithm, in which the control law constitutes of two parts i.e. equivalent control and switching control law [21]. The equivalent control is responsible for enforcing system trajectories towards sliding manifold and is designed after selecting sliding surface expressed in (3) [22].

$$\zeta(e) = \Big(\frac{d}{dt} + \lambda\Big)^{n-1} e \quad (3)$$

where λ is a tuning parameter, n is relative degree of system and e is tracking error variable. In type 1 diabetes patients, the control problem is the tracking of basal glucose level. Thus tracking error can be written as $e = x_1 - G_b$. By substituting $n = 3$, (3) can be rewritten as

$$\zeta(e) = \ddot{e} + \lambda^2 e + 2\lambda\dot{e} \quad (4)$$

Taking derivative of sliding manifold (4), we obtain

$$\dot{\zeta}(e) = \dddot{e} + \lambda^2\dot{e} + 2\lambda\ddot{e} \quad (5)$$

Thus error dynamics can be written as

$$\dot{e} = \dot{x}_1 - \dot{G}_b \quad (6)$$

where $\dot{G}_b = 0$, so (6) becomes;

$$\dot{e} = -\big(\alpha_1 + x_2\big)x_1 + \alpha_1 G_b + D(t) \quad (7)$$

$$\ddot{e} = -\alpha_1\dot{x}_1 - \dot{x}_2 x_1 - \dot{x}_1 x_2 + \dot{D}(t) \quad (8)$$

$$\dddot{e} = \dddot{x}_1 - \dddot{G}_b \quad (9)$$

where $\dddot{G}_b = 0$, thus (9) can be written as

$$\dddot{e} = \dddot{x}_1 \quad (10)$$

Using (7), (8) and (10), (5) can be rewritten as,

$$\dot{\zeta}(e) = \vartheta - \alpha_3 x_1 u + 2\lambda\ddot{e} + \lambda^2\dot{e} \quad (11)$$

where

$$\vartheta = \Big\{-\alpha_1\big(\alpha_1^2{+}3\alpha_3 I_b\big){-}\alpha_3 I_b\big(\alpha_2{+}n\big)\Big\}x_1{+}\Big\{-\alpha_1^2\big(1{+}G_b\big) +\alpha_1\alpha_2\big(2G_b{-}1\big){+}2D\big(\alpha_2{+}\alpha_1\big)\Big\}x_2{+}\Big\{-2\alpha_3\big(\alpha_1{+}D\big)\Big\}x_3{+} \Big\{-\alpha_1^2\big(1{+}G_b\big){+}\alpha_1\alpha_2\big(2G_b{-}1\big){+}2D\big(\alpha_2{+}\alpha_1\big)\Big\}x_2{+}\Big\{-2\alpha_3\big(\alpha_1 +D\big)\Big\}x_3{-}\Big\{\big(\alpha_1{+}\alpha_2\big)^2{-}3\alpha_3 I_b\Big\}x_1x_2{+}\Big\{\alpha_3\big(3\alpha_1{+}\alpha_2{+}n\big)\Big\} x_1x_3{+}\Big\{-3\big(\alpha_1{+}\alpha_2\big)\Big\}x_1x_2^2{+}\big(\alpha_1 G_b{+}D\big)x_2^2{+}3\alpha_3 x_1x_2x_3{-}x_1x_2^3 + \ddot{D} + \big(\alpha_1 G_b + D\big)\big(\alpha_1^2 + 2\alpha_3 I_b\big)$$

u_{equ} can be formulated by putting $\dot{\zeta}(e) = 0$ in (11), i.e.

$$u_{equ} = \frac{1}{\alpha_3 x_1}\Big(\vartheta + 2\lambda\ddot{e} + \lambda^2\dot{e}\Big)$$

The switching control law control law is responsible for directing the system trajectories on to sliding surface towards origin. This control law is based on super twisting control algorithm in the present study. The motivation factor behind the choice of control law lies in the fact that traditional SMC suffers from chattering phenomena [23] and exhibits unfavourable performance because of discontinuous control action in switching control law, which can be dangerous in practical applications [24]. Alleviation of chattering phenomena can be promised by using super twisting control algorithm, because of continuous nature of the associated control law [25].

The switching control law using super twisting control algorithm can be formulated as [26];

$$u_{sw} = \frac{1}{\alpha_3 x_1}\Big\{\beta_1|\zeta(e)|^{0.5} sign(\zeta(e)) + \beta_2\int sign(\zeta(e))d\tau\Big\},$$

where β_1 and β_2 are the controller gain parameters that can be selected by trial and error approach. Moreover, sign function $sign(\zeta(e))$ can be expressed as

$$sign(\zeta(e)) = \left\{\begin{matrix} 1 & for & \zeta(e) > 0 \\ -1 & for & \zeta(e) < 0 \end{matrix}\right\}$$

The final control input obtained can be expressed as given in (12)

$$u = \frac{1}{\alpha_3 x_1}\Big\{\vartheta + 2\lambda\ddot{e} + \lambda^2\dot{e} + \beta_1|\zeta(e)|^{0.5} sign(\zeta(e)) + \beta_2 \int sign(\zeta(e))d\tau\Big\}. \quad (12)$$

The control input in (12) is used to achieve the optimal value of glucose under hyperglycemia in type 1 diabetes patient even in the presence of external perturbations. To determine stability of non-linear system, Lyapanov Candidate Function (LCF) $\psi(x)$ is considered, which can be expressed as

$$\psi(x) = \frac{1}{2}\zeta(e)^2 \quad (13)$$

According to Lyapunov stability theorem 1, LCF must possess the following properties to guaranty stability of the closed loop system.

$$\begin{cases} \psi(x) \geq \quad 0 & for \quad all \quad x \\ \psi(x) \longrightarrow \infty & for \quad x \longrightarrow \infty \\ \dot{\psi}(x) \leq \quad 0 & for \quad all \quad x \end{cases}$$

To confirm if LCF satisfies the necessary conditions for stability, its time derivative needs to be considered and is given as,

$$\dot{\psi}(x) = \zeta(e)\Big\{\vartheta - (\vartheta + 2\lambda\ddot{e} + \lambda^2\dot{e} + \beta_1|\zeta(e)|^{0.5}sign(\zeta(e)) + \beta_2 \int sign(\zeta(e))d\tau\big) + 2\lambda\ddot{e} + \lambda^2\dot{e}\Big\}$$

or

$$\dot{\psi}(x) = \zeta(e)\Big\{ - \beta_1|\zeta(e)|^{0.5}sign(\zeta(e)) - \beta_2 \int sign(\zeta(e))d\tau\Big\}$$

$$\dot{\psi}(x) = \Big\{ - \beta_1|\zeta(e)|^{0.5}|\zeta(e)| - \beta_2 \int |\zeta(e)|d\tau\Big\} \tag{14}$$

The time derivative of LCF in (13) is negative definite, thus satisfying the conditions for stability provided by lyapunov stability theorem. It is quite clear that using appropriate values of the design parameters in the proposed control algorithm, the system output (glucose concentration in blood plasma) converges asymptotically towards the basal value of glucose in a finite time even under the influence of external disturbance.

IV. Simulation Results and Discussion

The performance of the proposed controller has been validated in simulations, which is carried out in MATLAB/Simulink running on on Dell laptop with x64 processor and 6GB RAM. Moreover, the comparative study of super twisting algorithm with traditional SMC is also investigated. The running parameters β_1, β_2 and λ in proposed control law are set to 0.7, 0.0000001 and 0.47 respectively.

The control objective is to regulate the glucose concentration such that it is kept closer to the basal value of glucose level in type 1 diabetes patients. This objective is achieved by designing a reliable controller based on non-linear super twisting algorithm. The controller has been designed for two different scenarios i.e. considering nominal system dynamics and dynamics with external perturbations. The control input is the output of the controller that regulates the amount of insulin delivered by a portable insulin infusion pump, thus developing an automated insulin system or artificial pancreas. An automatic insulin system is composed up of a glucose monitoring sensor, a controller and insulin infusion pump. These three parts operate in a close loop topology to form an integrated system. The initial conditions of states variables in both nominal and perturbed systems are chosen as $[220, 0, 50]^T$.

A. Desired Trajectory Tracking of System Without Any External Perturbations

The desired trajectory to be tracked by the proposed controller is the optimal value of glucose concentration in blood plasma, which is constant value $80mg/dl$. Considering a nominal system, the concentration of glucose in blood plasma of type 1 diabetes patient during hyperglycaemia is illustrated in Fig. 4. It is demonstrated that the proposed control scheme drives the glucose level from $220mg/dl$ to the optimal level in 400 min, while traditional SMC accomplished the same task in approximately 600 min.

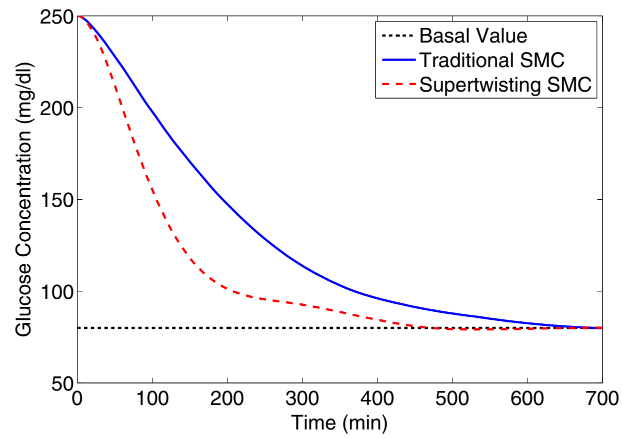

Fig. 4. Tracking of glucose optimal value in diabetes patient

Fig. 5 shows the behavior of tracking error during hyperglycemia. Tracking error is the difference between actual and basal values of glucose level. Initially, during hyperglycemia the maximum tracking error is observed, which is reduced to zero in approximately 400 min using the proposed control scheme, whereas it takes 550 min for traditional SMC to settle down its tracking error to zero. Thus, the super twisting control algorithm has much better performance than traditional SMC.

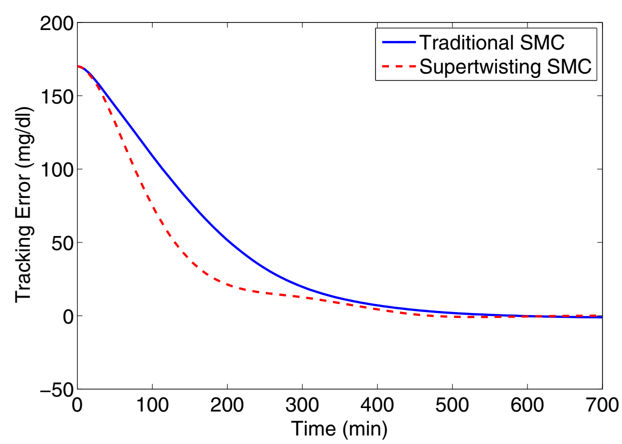

Fig. 5. Tracking error between actual and basal value of glucose

In Fig. 6, the corresponding control efforts are demonstrated. It is clearly illustrated that the proposed controller provides smooth infusion of insulin into patient body without fluctuations. However, in traditional SMC, the control input possess undesirable oscillations, which is hazardous in practical applications as mentioned earlier.

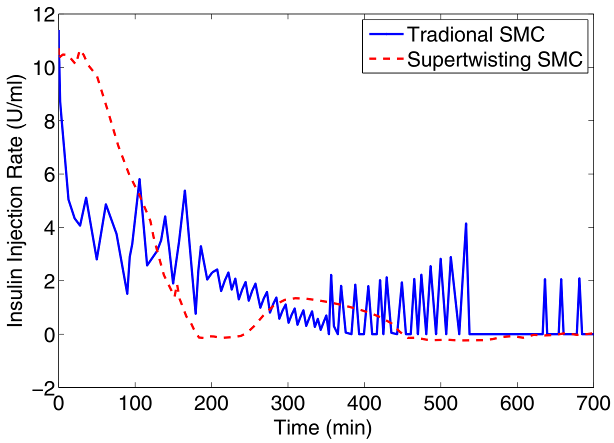

Fig. 6. Control input required for achieving the basal value of glucose

B. Tracking of Desired Trajectory by System With External Perturbations

To validate the robustness of the proposed controller, an external disturbance $D(t)$, which is basically glucose dosage, is injected to the system at $t = 6000$min. Fig. 7 depicts the performance of super twisting control algorithm during hyperglycaemia under the influence of external disturbance. It is clearly demonstrated that using the proposed controller the basal value of glucose concentration is achieved even under the influence of disturbance, thus validating the effectiveness as well as excellent robustness of the proposed controller. Moreover, the comparison with traditional SMC is also provided.

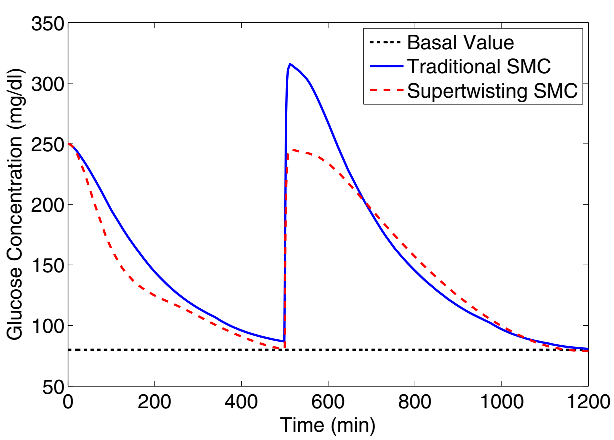

Fig. 7. Tracking of glucose optimal value in diabetes patient under external disturbances

In Fig. 8, the behavior of tracking error in the presence of external disturbances is illustrated. Initially, when the system is nominal, tracking error is minimum. When sudden disturbance is injected into the system at $t = 600$ min, the glucose level rapidly rises to $120mg/dl$. This is optimized by the proposed controller using infusion of insulin into patient, thus providing robustness by minimizing error to zero again at $t = 1200$ min.

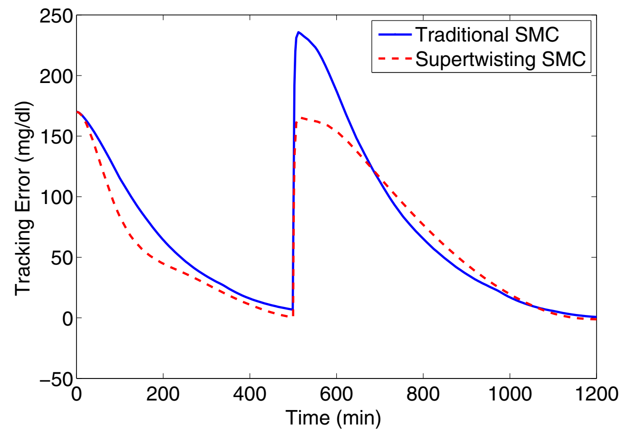

Fig. 8. Tracking error between actual and basal value of glucose under external disturbance

Fig. 9 depicts the control input in the presence of external disturbance. It is clearly illustrated that using super twisting control scheme, the control efforts made are less, smooth and having no fluctuations, while in case of traditional SMC, the control input is affected of the undesired chattering.

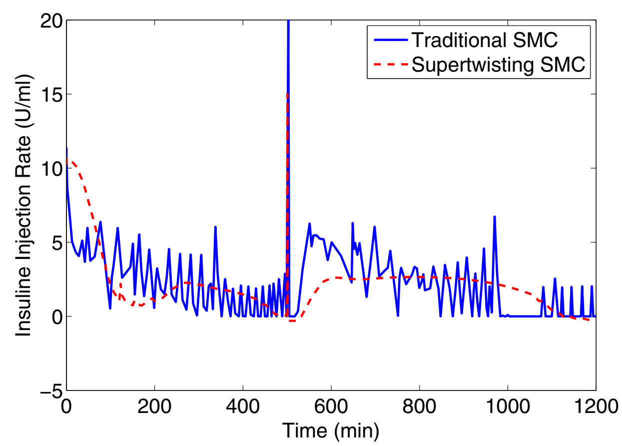

Fig. 9. Control input required for achieving the basal value of glucose in perturbed situation

V. Conclusion

In this article, super twisting control algorithm based on a robust non-linear SMC approach has been investigated to maintain the basal value of glucose concentration in type 1 diabetes patient. The proposed control scheme ensured the accurate tracking of glucose optimal level in blood plasma, so as to converge the tracking error asymptotically in a finite time. The design procedure of aforementioned control scheme incorporated various non-linearities in the system. The effectiveness of the proposed algorithm is also examined under the influence of external disturbance. It is observed that, in the presence of external perturbation, the controller is capable to retain the nominal performance of the system, thus ensuring excellent robustness. Moreover, the simulation based comparative analysis of the proposed control algorithm with traditional SMC is also carried out, which proved the effectiveness of proposed control scheme for type 1 diabetes patients. In future, it is planned to estimate noise and mitigate its effect and to further reduce chattering. Also, fault tolerance in the proposed control scheme is anticipated in near future.

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