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Fractional Order PID Controller for Diabetes Patients

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Abstract

This paper proposes an optimized control policy over type one diabetes. Type one diabetes is taken into consideration as a nonlinear model (Augmented Minimal Model), which is implemented in MATLAB-SIMULINK. This Model is developed in consideration of the patient's conditions. There are some uncertainties in the regarded model due to factors such as blood glucose concentration, daily meals or sudden stresses. Moreover, there are distinct approaches toward the elimination of these uncertainties. In here, a meal is fed to the model as an input in order to omit these uncertainties. Also, different control methods could be chosen to monitor the blood glucose level. In this paper, a Fractional Order PID is utilized as the control method. Thereafter, the control method and parameters are tuned by conducting genetic algorithm, as a powerful evolutionary algorithm. Finally, the output of the optimized Fractional order PID and traditional PID control method, which had the same parameters as the Fractional PID except the fractions, are compared. At the end, it is concluded by utilizing Fractional Order PID, not only the controller performance improved considerably, but also, unlike the traditional PID, the blood glucose concentration is maintained in the desired range.

Keywords: *diabetes, fractional order PID, genetic algorithm.*

1. Introduction

Diabetes is a group of metabolic disease which defects in insulin production, insulin action or both cause high levels of blood glucose concentration. Diabetes is the leading cause of nontraumatic lower limb amputation, kidney failure and a major cause of heart disease and stroke. Number of diabetic patients is unfortunately on rise [1,2]. One of the recommended therapies for type 1 diabetes by American Diabetes Association (ADA) is using multiple-dose insulin injections (three to four injections per day of basal and prandial insulin) [3]. It is lifesaving to keep blood glucose concentration as close as possible to the normal range in diabetic patients. Also, accurate control of blood glucose concentration control yields in preventing or slowing down the progress of diabetes [4]. Moreover, it was shown in order to affect plasma cholesterol and LDL cholesterol levels, strict metabolic control is required [5]. Therefore, precise controlling of blood glucose concentration, is a crucial

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subject and has drawn the attention of many to the subject [6,7].

PID (proportional-integral-derivative) controller is a powerful control strategy, that minimizes the difference between a set value and process variables [8]. Robustness, simplicity and wide range of applicability are the main reasons of PID controllers wide usage [9]. Tuning procedure and determining the optimal proportional, integral and derivative parameters is a critical issue in PID controllers [10]. In order to overcome these difficulties automatic tuning of PID controllers has been thoroughly studied by researchers [11-13]. In addition, to improve PID controller's steady state and transient performance fractional order PID controllers were introduced and implemented [14]. A favorable control policy requires a vast amount of knowledge and experience. In order to evade this problem, studies have been carried out to design fractional PID controllers needless of an expert's experience and knowledge, by utilization of genetic algorithm [15]. Researches have been undertaken to control blood glucose concentration in type 1 diabetics by the means of PID controllers and it was proven to be efficient though not totally effective, due to its undesirable over shoot and settling time which could result in some drastic effects on diabetics subjects [16,17]. Moreover, Fractional PID has not been conducted in type 1 diabetics control yet. In this paper we propose a novel fractional PID controller, to accurately control blood glucose concentration in type 1 diabetes. In Section 2, a nonlinear diabetes model is introduced. In Section 3, we focus on Fractional Order PID controller and its implementation. The novelty of this work is presented in Sections 4, where the fractional PID controller is tuned by genetic algorithm.

2. Augmented Minimal Model

Since the case of type one polygenic disease is widely studied and its physiological causes are relatively clear, the eye of the tutorial community has been centered on modeling and understanding of type two polygenic diseases (see [14]). One amongst the goals of this study are to demonstrate the profits of explaining the aldohexose metabolism of type one diabetics with one stripped-down model (the Augmented Minimal Model in this case). The coupled nonlinear set of equations are given below [18].

$$\begin{cases} \dfrac{dI}{dt} = -\gamma_I .I(t) + \beta.\max[G(t) - \theta_I, 0] + D_I(t) \\ \dfrac{dN}{dt} = -\gamma_N .N(t) + \alpha_N .\max[\theta_N - G(t), 0] \\ \dfrac{dX}{dt} = -P_2 .X(t) + P_3 .I(t) \\ \dfrac{dG_I}{dt} = -P_1 G_I(t) - X(t)G(t) \\ \dfrac{dG_N}{dt} = -P_4 .G_N(t) + P_5 .N(t) \\ G(t) = G_b + G_I(t) + G_N(t) + D_G(t) \end{cases} \quad (1)$$

The augmented minimal diabetes model parameters were introduced in Table 1 and the input, output or desired values of these parameters were given in the same table as well. Also, the AMM state parameters for a healthy person and diabetic patients type 1 and 2 is given in Table 2.

Table 1. Nomenclature [18]

I	value deviation of plasma insulin concentration from its basal	15 mU/L in healthy subjects
N	value deviation of plasma glucagon concentration from its basal	75 ng/L in healthy subjects
X	insulin action	min%
G_I	value due to insulin action deviation of blood glucose concentration from its basal	mg/dL
G_N	value due to glucagon action deviation of blood glucose concentration from its basal	mg/dL
G_b	basal value of blood glucose concentration	assumed 90mg/dl in this study
G	concentration of blood glucose	mg/dL
D_I	insulin disturbance	mU/L/min
D_G	glucose disturbance	mg/dL

Table 2. AMM Parameters For Healthy And Diabetics Subjects [18]

	Healthy	Type 1	Type 2
γ_I	[0.43,0.56]	N/A	0.42
β	$[9\times10^{-4},0.08]$	0	0.106
θ_I	[101,114]	N/A	103
γ_N	$[4.5\times10^{-4},9.5\times10^{-4}]$	$[0,1.2\times10^{-3}]$	5.8×10^{-4}
α_N	[0.0023,0.0049]	$[4\times10^{-4},1.2\times10^{-3}]$	0.0037
θ_N	[77,91]	[75,93]	83
P_1	[0.004,0.036]	0.013	0.022
P_2	[0.034,0.155]	0.063	0.075
P_3	$[3.1\times10^{-6},1.3\times10^{-5}]$	910-6	1.3×10^{-5}
P_4	[0.027,0.05]	0.04	0.04
P_5	[0.015,0.017]	0.016	0.016

Figure 1, shows the implementation of AMM nonlinear model in MATLAB-SIMULINK setting. As it can be seen in Table 2 the parameters are given as ranges, Table 3 illustrates the exact values of parameters that were implemented as function block parameters in diabetics. As it can be concluded from set of Equations (1), the internal secretion concentration varies with time by internal secretion injection. As a result, the blood glucose concentration varies with time, severally. Therefore, a powerful control method is needed to maintain the blood glucose concentration in the normal range in diabetic patients. It should be mentioned that the desired blood glucose concentration value in normal operating condition is 110 mg/dL and when this value exceeds 140 mg/dL impaired glucose tolerance occurs [19]. Table 4 illustrates the normal values of blood glucose concentration in type one diabetics patients.

In Figure 2 the concentration of glucose in the absence of the controller is demonstrated when a meal is fed to the system. As we would expect, the blood glucose concentration initially experiences a harsh increase, this phenomena will be proved later. As it is clear in Figure 2 after a meal blood glucose exceed 161 mg/dL which is a life hazard. If the patient survives the first 200 minutes after the meal, the concentration of blood glucose will gradually decrease. However, its value will not reach the desired range (110-140 mg/dL), as it can be seen in Figure 2 even after 1000 minutes the blood glucose level is higher than 180 mg/dL which is a critical and dangerous condition for the patient.

Table 3. Function Block Parameters In Diabetics [18]

G_b	γ_I	β	θ_I	γ_N	α_N
110	0.56	0.08	114	9.5e-4	0.0049
θ_N	P_1	P_2	P_3	P_4	P_5
91	0.036	0.155	1.3e-5	0.05	0.017

Table 4. Blood Glucose Concentration Levels In Diabetics Type 1, Before And After A Meal [19]

Diabetic type 1 normal blood glucose concentration range		
Before a meal	4-7 mmol/L	72-126 mg/dL
Operating normally	4.4-6.1 mmol/L	82-110 mg/dL
After a meal	Up to 9 mmol/L	Up to 161 mg/dL

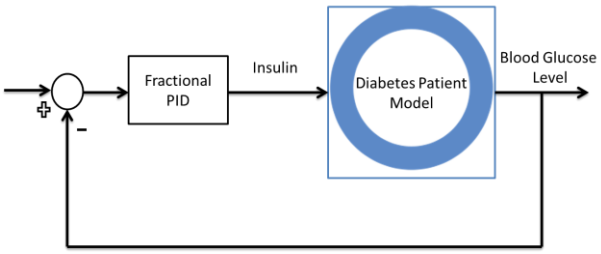

Fig. 1. Diabetes aggregated model with an input box control, an input and an output noise

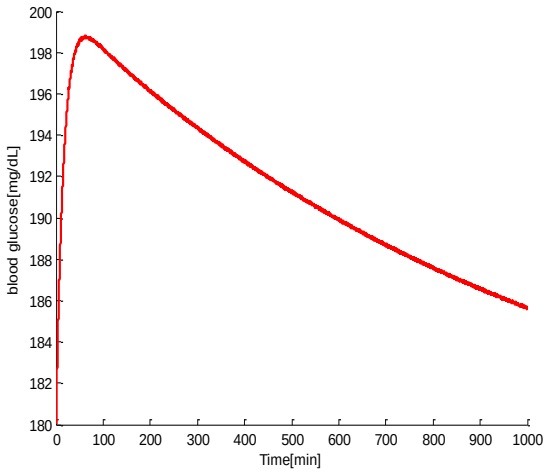

Fig. 2. Concentration of glucose after a meal in the absence of the controller

3. FOPID Controller

To study the fractional order controllers, the starting point is of course the fractional order differential equations using fractional calculus. A commonly used definition of the fractional differ integral is the Riemann-Liouville definition [20].

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt}\right)^m \int_0^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \qquad (2) $$

For m − 1 <α<m where Γ(0) is the well-known Euler's gamma function. An alternative definition, based on the concept of fractional differentiation, is the Grunwald-Letnikov definition given by

$$ {}_aD_t^{\alpha} f(t) = \lim_{h \to 0} \frac{1}{\Gamma(\alpha) h^{\alpha}} \sum_{k=0}^{(t-\alpha)/h} \frac{\Gamma(\alpha + k)}{\Gamma(k+1)} f(t - kh) \qquad (3) $$

In Equations (3) and (4), there are some parameters which are defined as below.

- α is the derivative order which be limited in an interval [-1 m]
- Γ is the well-known gamma function
- t is the time
- f is the purpose function
- τ is the integral variable
- h is a short interval which derivative occurs

One can observe that by introducing notion of the fractional order operator ${}_aD_t^{\alpha} f(t)$ the differentiator and integrator can be unified. Another useful tool is the Laplace transform. It was shown in [13] that the Laplace transform of an nth (n ∈ R+) derivative of a signal x(t) relaxed at t=0 is given by $L\left\{D^n x(t)\right\} = s^n X(s)$. So, a fractional order differential equation, provided both the signals u(t) and y(t) are relaxed at t =0, can be expressed in a transfer function form

$$ G(s) = \frac{a_1 s^{\alpha_1} + a_2 s^{\alpha_2} + \ldots + a_m s^{\alpha_m}}{b_1 s^{\beta_1} + b_2 s^{\beta_2} + \ldots + b_m s^{\beta_m}} \qquad (4) $$

where

$$ (a_m, b_m) \in R^2, (\alpha_m, \beta_m) \in R^2, \forall (m \in N) $$

$$ G_c(s) = K_p + \frac{K_I}{s^{\lambda}} + k_D s^{\mu} \qquad (5) $$

The integrator term is s^{λ} that is to say, on a semi-logarithmic plane, there is a line having slope −20λdB./dec. The control signal u(t) can then be expressed in the time domain as

$$ u(t) = k_p e(t) + k_I D^{-\lambda} e(t) + k_D D^{\mu} e(t) \qquad (6) $$

Clearly, selecting λ =1 and μ =1, a classical PID controller can be recovered. The selections of λ =1, μ =0, and λ =0, μ =1 respectively corresponds conventional PI & PD controllers. All these classical types of PID controllers are the special cases of the fractional $PI^{\lambda}D^{\mu}$ controller given by (5). It can be expected that the $PI^{\lambda}D^{\mu}$ controller may enhance the systems control performance. One of the most important advantages of the $PI^{\lambda}D^{\mu}$ controller is better control over dynamical systems, which are described by fractional order mathematical models. Another advantage lies in the fact that the $PI^{\lambda}D^{\mu}$ controllers are less sensitive to changes of parameters of a controlled system [21]. This is due to the two extra degrees of freedom to better adjust the dynamical properties of a fractional order control system. However, all these claimed benefits were not systematically demonstrated in the literature. In this paper, from a practical point of view, we attempt to illustrate the benefits in a reproducible manner. It was pointed out in [22] that a band-limit implementation of fractional order controller is important in practice, and the finite dimensional approximation of the fractional order controller should be done in a proper range of frequencies of practical interest. This is correct since the fractional order controller in theory has an infinite memory and some sort of approximation using finite memory must be done.

Genetic algorithm is a special type of evolutionary algorithms, which uses reverted biology techniques such as inheritance and mutation to introduce new genes (solutions). In fact, genetic algorithms utilize Darwin's principle of natural selection to find the optimal formula for predicting or matching patterns. Genetic algorithm is a good option for prediction based on regression techniques. In another saying, genetic algorithm is a programming technique which employs genetic evolution as a problem-solving model. The problem, which has to be solved, is the input and solutions are coded according to a pattern that is called fitness function. Each solution evaluates the candidate, while most of them are randomly selected. The flowchart of this algorithm is illustrated in Figure 3; also the assigned variables to implement the method in MATLAB are available in Table 5.

The cost function used to tune the FOPID parameters is given in Equation (7). This criterion is called ITAE (Integral Time Absolute Error).

$$ J = \int_0^{1000} (G_d - G)^2 t dt \qquad (7) $$

Table 5. Properties Of The Conducted Genetic Algorithm

Option	Value
Crossover function	Heuristic
Crossover fraction	0.8
Elite number	2
Initial penalty	10
Mutation function	Adaptive feasible
Penalty factor	100
Population initial range	[-1,1]
Population size	100
Population type	Bit string
Selection function	Stochastic uniform

Selection is the stage of a genetic algorithm in which individual genomes are selected from a population for later refinement (mutation or crossover). The flow chart depicted in Figure 3, selection procedure was divided to mutation and crossover step where mentioned in the Table 5 and also the selecting type was chosen as stochastic uniform. The initial penalty number, penalty factor and elite number are used in the converging criterion process. The large penalty factors do not allow the invalid results to stay alive for long through the GA evolution, as they are not likely to be selected for reproduction as a result of their non-proper quality. Meanwhile, the optimization was done utilizing MATLAB optimization toolbox.

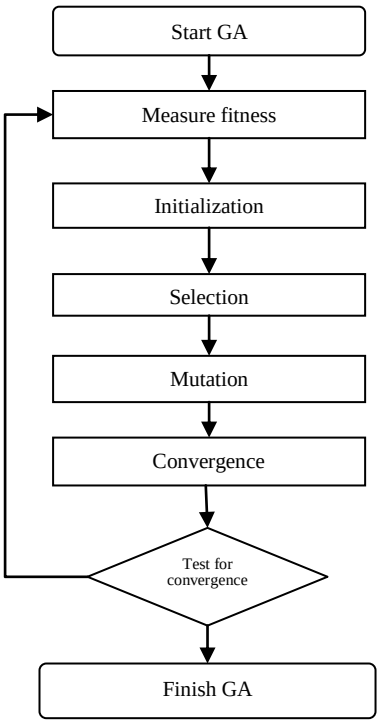

Fig. 3. Biological Genetic algorithm process flow

4. Simulation and Results

As it can be seen in Figure 6, one of the processes in this study, was converged at the 92nd generation, where the fitness function reached its minimum. At this point, the novel findings of this study were reported in Table 5 where the fractional order PID parameters are given. The results of this procedure with the exception of λ and μ are considered for the traditional PID controller, which later will be compared with our proposed FOPID controller. Because of the random behavior genetic algorithm foe selecting initial value, several attempts was made to achieve the best results. As Table 6 shows, the first try is the proper selection.

Table 6. Optimized FOPID parameters

	First try	second try	third try	fourth try
Kp	-2	-1.92983	-1.99987	-1.9578
Kd	-0.99803	-0.99742	-0.99699	-0.9921
Ki	-2	-1.96004	-1.97332	-1.96024
μ	0.000768	0.005098	0	0.011792
λ	-0.01001	-0.01847	-0.01	-0.01425
CFV	2.14E+09	2.28E+09	2.15E+09	2.15E+09

* CFV: cost function value

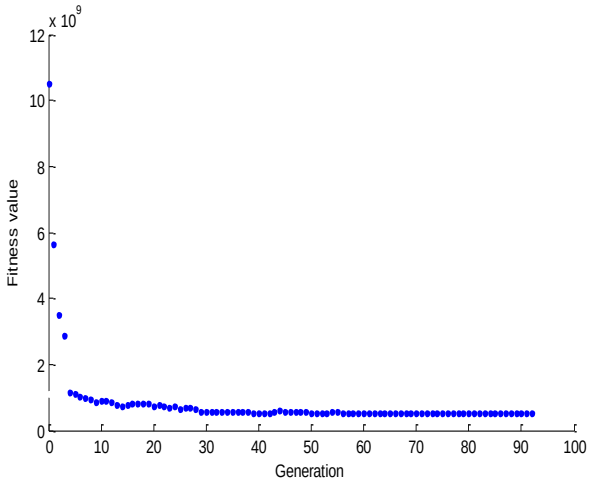

Fig. 4. Genetic algorithm generations

Figures 5 and 6 show the blood glucose level control and insulin injected using both traditional and fractional PID controller respectively. Considering that the normal range for blood glucose concentration is 110-140 [mg/dL], it can be seen in Figures 5.a and 5.b, FOPID is capable of controlling the glucose level, while the traditional PID failed in this

procedure. This happened via the existence of μ and λ which adjust the magnitude of control effort for derivative and integrative orders. Also, as Figures 6.a and 6.b show, the insulin injected by FOPID is much more logical than traditional PID injection.

To show the power of the fractional PID controller, the optimized traditional PID and the proposed fractional PID are compared with each other in Figure 7. The gains achieved from the genetic algorithm for traditional PID are KP (-6.11122), Kd (2.25231) and ki (-0.2633). As Figure 7 shows, the optimized PID controller can control the blood glucose as well. Whereas, the FOPID is not as powerful as the optimized PID. Nevertheless, the insulin injected by optimized PID is not as smooth as FOPID. As the Figure 8 shows, the PID controller has a chattering behavior in its procedure. Whereas the optimized fractional PID controller could inject the insulin efficiently. This fact is due to the releasing the derivative order values.

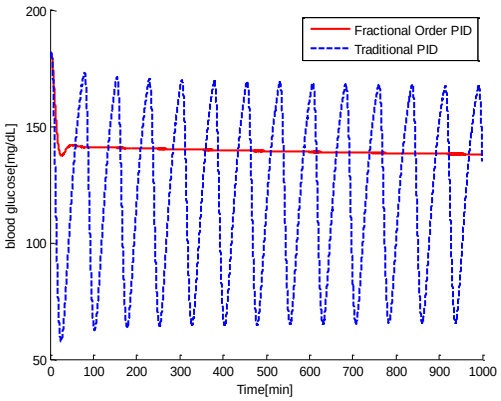

Fig. 5. a) Blood glucose level variation with time, using PID and FOPID controllers

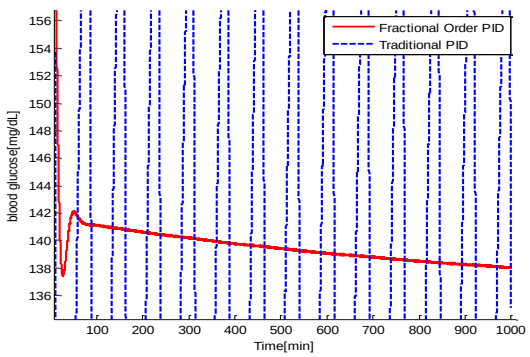

Fig. 5. b) Blood glucose control in traditional PID and FOPID (Zoomed)

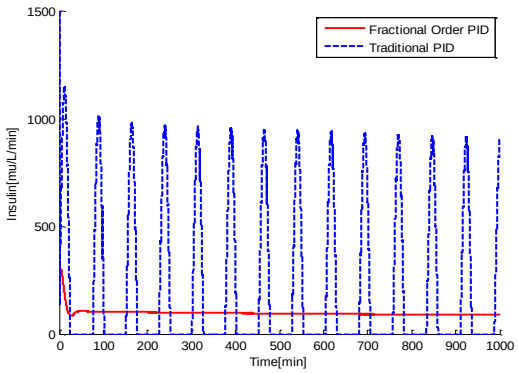

Fig. 6. a) Insulin injection using PID and FOPID

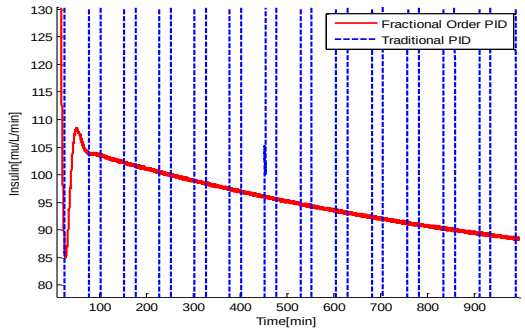

Fig. 6. b) Insulin injection using PID and FOPID (zoomed)

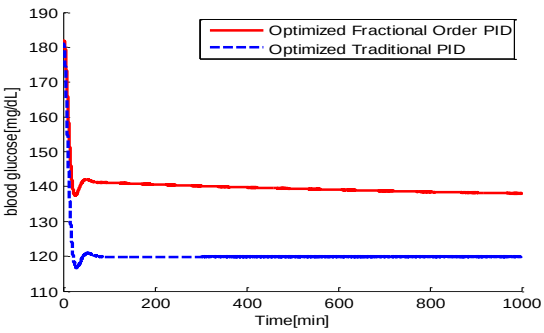

Fig. 7. Comparing blood glucose control using optimized PID and FOPID

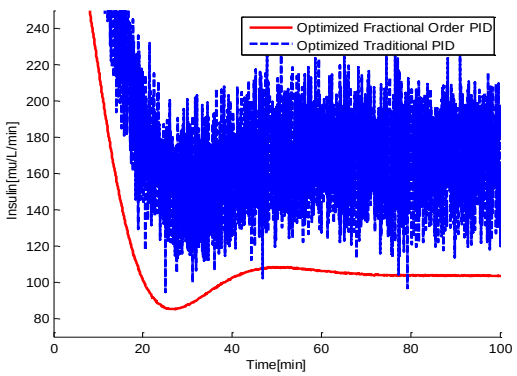

Fig. 8. Comparing insulin injecting rate using optimized PID and FOPID

5. Conclusion

In this paper, a nonlinear model based on minimal augmented model had been used to simulate the 1st type of diabetes. In order to regulate the blood glucose level a fractional order PID controller was employed. The parameters of this controller were tuned by genetic algorithm. Afterward, a comparison was made between FOPID and traditional PID. The FOPID showed a negligible deviation from the desired blood glucose concentration range, in contradictory traditional PID even failed to stabilize the blood glucose concentration. To conclude, as we proved here, FOPID can serve as an effective and powerful controller in the case of type 1 diabetes and could reduce its drastic effects on diabetic patients.

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