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AUTONOMOUS HUMAN BODY CONTROL, PART III: TYPE 1 BLOOD GLUCOSE CONTROL USING PD AND 2DOF-3 CONTROLLERS COMPARED WITH PID AND FRACTION ORDER-PID CONTROLLERS

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ABSTRACT

This paper is the third in a series of research papers presenting the autonomous control of the human body. It handles the control of type 1 blood glucose using PD and 2DOF-3 controllers from the first and second generations of PID controllers. The proposed controllers are tuned using multiple approaches including zero/pole cancellation, specific performance characteristics fulfillment and MATLAB optimization toolbox. The step time response of the control system using the two proposed controllers is presented and compared with using a PID and FO-PID controllers to control the same patient dynamic characteristics and the time-based characteristics are compared. The comparison reveals the best controller among the four controllers depending on a graphical and quantitative comparison study.

KEYWORDS: Autonomous human body control, blood glucose control, PD controller, 2DOF-3 controller, PID controller, FO-PID controller, controllers tuning.

INTRODUCTION

Millions of people around the world are suffering from high blood glucose (hyperglycemia above 180-200 mg/dL.[1]) or low blood glucose (hypoglycemia below 70 mg/Dl.[2]). Some symptoms of hyperglycemia are: frequent urination, increased thirst, blurred vision,

unusually tired, dry mouth, abdomen pain, nausea and vomiting, shortness of breath, confusion and loss of consciousness.[1] On the other hand, some symptoms of hypoglycemia are: shaking, extreme hunger, tingling, slurred speech, seizures and loss of consciousness.[2]

This means that the situation is dangerous and the human being is between a hyperglycemia or hypoglycemia and a need to control the blood glucose is ultimately required to save the life of the human being. This is the objective of this research paper, but first of all we will have a look into some of the international research regarding this important aspect since 2012.

Schmidt et al. (2012) designed and discussed an algorithm for overnight closed-loop control of blood glucose in people with type 1 diabetes. Their algorithm was based on model predictive control and used an offset-free autoregressive model with exogenous input and moving average to model the patient. They used a second-order transfer function model for the blood glucose with equal poles.[3] Anilkumar and Phadke (2014) designed a digital PID controller based on field programmable gate array device to regulate blood glucose level of diabetic patients. They used the Ziegler-Nichols technique to tune the controller in MATLAB and simulink environment. They used a second-order + integrator transfer function model for the blood glucose and presented the step time response to a unit step input for PI and PID controllers with about 45 % and 65 % maximum overshoot respectively.[4]

Soylu and Danisman (2016) proposed three control strategies as controllers for blodd glucose control: genetic algorithm-PID, artificial bee colony-PID and particle swarm optimization-PID. They demonstrated controller robustness through implementing a noise test.[5] Jain, Agrawal and Sharma (2017) designed a digital PID controller to control the blood glucose level of a diabetic patient. They used Ziegler-Nichols (Z-N) and Cohen-Coon (C-C) to tune the controller. They used a second-order + integrator transfer function model and provided a unit step time response for the control system using both tuning techniques having maximum overshoot of 26.67 and 25.30 % for Z-N and N-N tuning techniques and 17.9 and 11.24 s settling time respectively.[6] Soylu and Danisman (2018) proposed a fuzzy controller tuned by the artificial bee colony optimization technique. They used a nonlinear dynamic model with time delay for virtual patient and a healthy person. They implemented three tests to examine the robustness of the controller and concluded that their controller was more effective than similar studies.[7] Betmani and Khadakaramzadeh (2020) evaluated a multiple-model strategy for subcutaneous insulin delivery in type 1 diabetes. They obtained five transfer functions for five operating points of the glucose-insulin dynamic system. They tuned five PID controllers

to achieve the required settling time, overshoot and undershoot. They claimed that their strategy lead to blood glucose control with limited hypoglycemia and hyperglycemia. They used 0/2 second-order transfer function models and tuned a PIDN controller for each of them.[8]

Batiha et al. (2021) used a fractional-order (FO) PID controller with two optimization algorithms (PSO and BFO) to design tune the controller. They used the glucose-insulin transfer function model of 0/2 order plus an integrator introduced in reference.[6] They claimed that the FO-PID with PSO algorithm and Oustaloup's approach was the best.[9] Saleem and Iqbal (2023) proposed a complex-order PID control strategy for robust blood glucose regulation in type I diabetes patients. They optimized the controller parameters offline numerically and applied the controller to track a set-point of 80 mg/dL from an initial state of hyperglycemia under various disturbance factors. They compared with a FO-PID controller achieving 13.1 % reduction in reference tracking error and 33.4 % in transient-recovery time.[10] Nisar and Farman (2025) developed a mathematical model exploring a complex dynamics of diabetes progression and control. They claimed that their model demonstrated improved accuracy over traditional integer-order models. They analyzed the chaotic behavior of their complex model using feedback control, controllability and PID techniques. They stabilized the chaotic glucose dynamics using a factional-order PID controller achieving more reliable blood glucose regulation compared with conventional methods (as their claim).[11]

Controlled Type 1 Blood Glucose

Jain, Agrawal and Sharma used a transfer function model for type 1 blood glucose in the form of a second-order plus one integrator transfer function.[6] As a controlled process, the transfer functions of it, $G_p(s)$ given by.[6]

$$G_p(s) = 1 / [s(s^2 + 6s + 5)] \quad (1)$$

The transfer function in Eq.1 represents an unstable dynamic system since it comprises a pole at origin.

Controlling the Type 1 Blood Glucose using a Conventional PID Controller

For sake of comparison with other controllers we start the analysis by considering two controllers used in previous research work to control the type 1 glucose diabetic using the same dynamic model defined by Eq.1. The first controller is a conventional PID controller

used in reference.[6] to control the type 1 glucose of a patient with Eq.1 model. A PID controller has the transfer function, $G_{PID}(s)$ given by:

$$G_{PID}(s) = K_{pc1}+(K_{i1}/s)+K_{d1}s \quad (2)$$

Where: K_{pc1} = proportional gain.

K_{i1} = integral gain.

K_{d1} = compensator derivative gain.

- They tuned the three gain parameters of the PID controller using the Ziegler-Nichols technique and have given its tuned parameters as.[6]

  $$K_{pc1} = 3.25316,\ K_{i1} = 0.882044,\ K_{d1} = 2.99957 \quad (3)$$

- Using the block diagram of the control system in a single-loop structure with controller coming after the error detector and cascaded by the controlled process, the transfer function is derived using Eqs.1,2 and 3 and the step time response of the control system using the step command of MATLAB.[12] given in Fig.1 for:

- Considering a diabetes type 1 patient having blood glucose (BG) of level state 200 mg/dL. This will be the reference of all the step time response values.
- The lower level of the normal BG is 72 mg/dL.[13] Relative to the 200 mg/dL initial state it becomes ΔLL=72-200 (i.e. -128 mg/dL).
- The upper level of the normal BG is 108 mg/dL.[13] Relative to the 200 mg/dL initial state it becomes ΔUL= 108-200 (i.e. -92 mg/dL).
- The desired BG set point is 100 mg/dL. Relative to the 200 mg/dL initial state it becomes ΔSP= 100-200 (i.e. -100 mg/dL).
- The above four tips are considered when drawing the above step time response with PID controller and with all the other controllers investigated in this research work.

COMMENTS

The conventional PID controller using the tuned parameters in Eq.3[6] provided a reference input tracking step time response having the following characteristics:

- Maximum percentage undershoot: 28.944 %
- Settling time within ± 2 % tolerance: 17.235 s
- Settling time within ΔLL and ΔUL: 6.100 s
- Steady-state error: zero

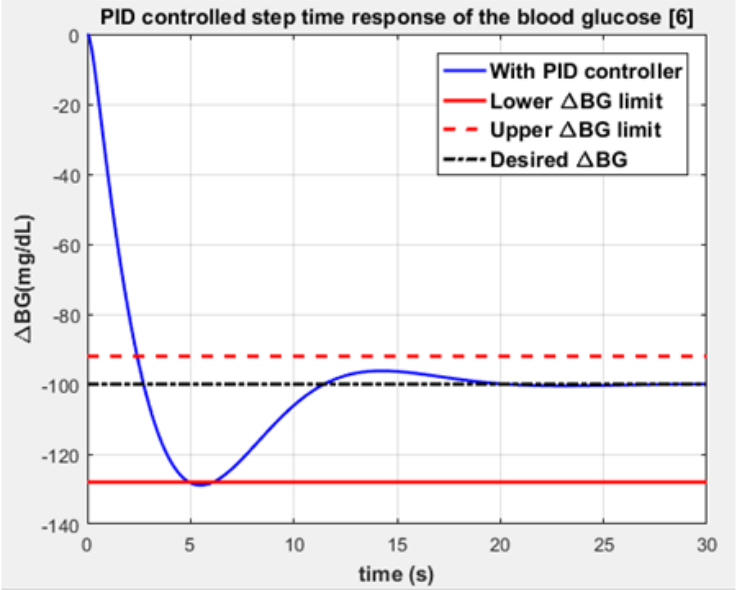

Figure 1: Step time response of the blood glucose using a PID controller.

Controlling the Type 1 Blood Glucose using a Fractional-order PID Controller

The fractional-order (FO)-PID controller was used by Batiha et al. to control type 1 diabetes patients.[9] They used two optimization techniques to tune the FO-PID controller: PSO and BFO techniques and the same patient transfer function model of Jain et al.[6]

- The step time response of the control system with the FO-PID controller was given by Batiha et al. for a unit step input for both PSO and BFO optimization algorithms.[9] Their step time response with BFO optimization for discretized and transformed to a desired glucose level of 100 mg/dL (-100 mg/dL change) and shown in Fig.2.

COMMENTS

The FO-PID controller provided a reference input tracking step time response having the following characteristics:

- Maximum percentage undershoot: 30.00 %
- Settling time within ± 2 % tolerance: 6.00 s
- Settling time within ΔLL and ΔUL: 1.50 s
- Steady-state error: zero

Controlling the Type 1 Diabetic using a Conventional PD Controller

The PD controller is one of the first generation of PID controllers applied and tuned by the author for second-order and third-order industrial processes.[14]-[16] The conventional PD controller has a transfer function $G_{PD}(s)$ given by:

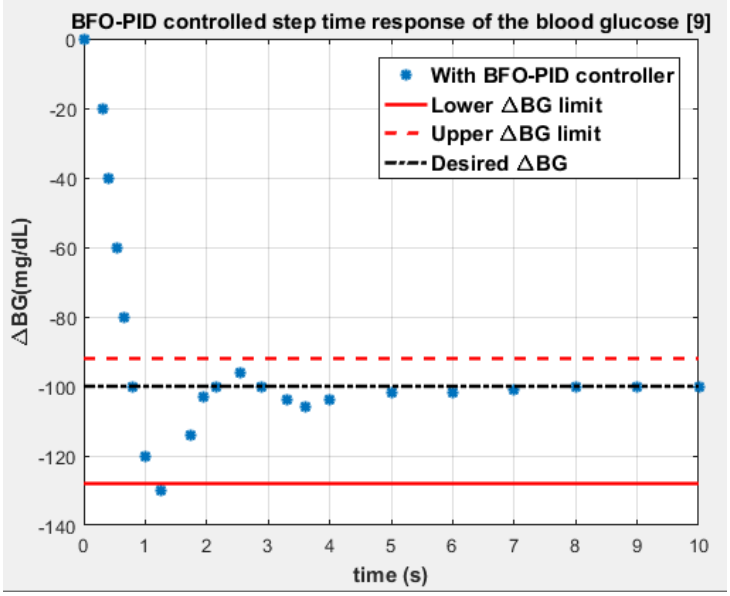

Figure 2: Step time response of the blood glucose using a FO-PID controller.

$G_{PD}(s) = K_{pc2} + K_{d2}s$ (4)

Where: K_{pc2} = proportional gain of the PD controller.

K_{d2} = derivative gain of the PD controller.

- The PD controller gain parameters (K_{pc2}, K_{d2}) have to be tuned to satisfy the objectives of using the controller to achieve type 1 glucose level control and provide good control system performance. It is tuned as follows:

- To facilitate the use of the zero/pole cancellation technique.[17] the blood glucose process transfer function in Eq.1 is to be written in the form of simple poles as in Eq.5 having two simple poles: (s+1) and (s+5):

  $G_p(s) = 1 / [s(s+1)(s+5)]$ (5)

- The transfer function of the PD controller in Eq.4 is written in the form of a simple zero as in Eq.6:

  $G_{PD}(s) = K_{d2}[s+(K_{pc2}/K_{d2})]$ (6)

- The open-loop transfer function of the control system incorporating then PD controller and the blood glucose process, $G_2(s)$ is given by the multiplication of the transfer function Eqs.5 and 6 giving:

  $G_2(s) = K_{d2}[s+(K_{pc2}/K_{d2})]/[s(s+1)(s+5)]$ (7)

- The process pole (s+1) of the blood glucose is closer to the origin. So, it results bad system dynamics. Using the zero/pole cancellation technique.[17] we equate the zero of

Eq.7 $s+(K_{pc2}/K_{d2})$ with the blood glucose pole s+1 revealing the following relationship between the two gain parameters of the PD controller:

$$K_{pc2} = K_{d2} \quad (8)$$

- Now, we can deduce the closed-loop transfer function of the control system incorporating the PD controller, $M_2(s)$ as:

$$M_2(s) = K_{d2}/(s^2+5s+K_{d2}) = \omega_n^2/(s^2+2\zeta\omega_n s+\omega_n^2) \quad (9)$$

- The dynamic system in Eq.9 is a standard second-order one having a natural frequency ω_n and a damping ratio ζ.
- The second tuning condition is eliminating completely the maximum undershoot. This is possible through the selection of a unit damping ratio (critical damping).[18] This condition using Eq.9 reveals the derivative PD controller gain as:

$$K_{d2} = 6.25 \quad (10)$$

- Now, Eq.9 is ready to plot the step time response of the control system for the desired blood glucose change of -100 mg/dL generated by the step command of MATLAB.[12] and shown in Fig.3.

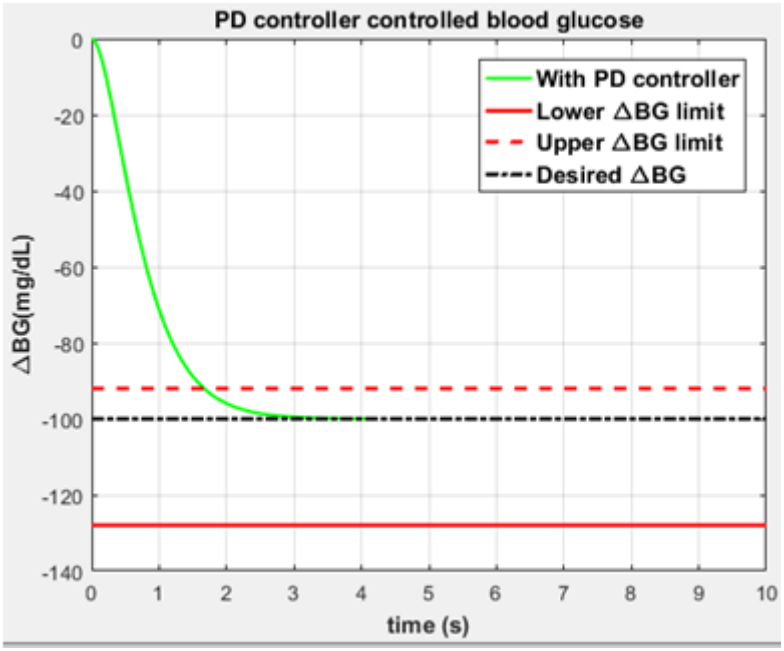

Figure 3: Step time response of the blood glucose using a PD controller.

COMMENTS

The conventional PD controller provided a reference input tracking step time response having the following characteristics:

- Maximum percentage undershoot: zero

- Settling time within ± 2 % tolerance: 2.333 s
- Settling time within ΔLL and ΔUL: 1.666 s
- Steady-state error: zero

Controlling the Type 1 Blood Glucose using a 2DOF-3 Controller

The 2DOF controller was introduced by the author to control a number of difficult processes since 2014 and used different structures of 2DOF control to control a variety of industrial processes having bad dynamics.[19] The structure of the 2DOF controller used in the present work is shown in Fig.4.[20] The 2DOF-3 controller is composed of two control elements having the same control mode structure for a PD control to simplify the analysis of the control system using the 2DOF control structure.[20]

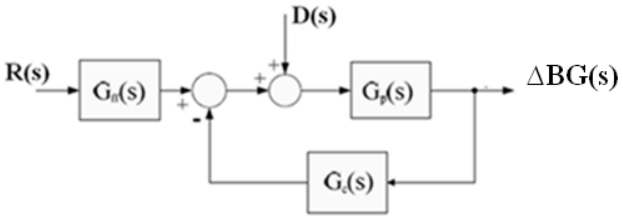

Figure 4: Type 1 blood glucose control using a 2DOF-3 controller.[20]

The transfer functions of the 2DOF-3 controller are as follows:

$$G_{ff}(s) = K_{pc3} + K_{d3}s$$

and $$G_c(s) = K_{pc4} + K_{d4}s \quad (11)$$

Where: K_{pc3} and K_{d3} = proportional and derivative gain parameters of the feedforward PD-control mode.

K_{pc4} and K_{d4} = proportional and derivative gain parameters of the feedback PD-control mode. The 2DOF-3 controller has four gain parameters to be tuned to provide the required performance of the closed-loop system of the type 1 blood glucose. The 2DOF-3 controller is tuned as follows:

- Using the block diagram in Fig.4, the open-loop transfer function is derived and the zero/pole cancellation technique.[17] is applied as in the tuning procedure of the PD controller yielding the relationship between K_{pc4} and K_{d4} as in Eq.8.
- Now, deriving the closed-loop transfer function of the closed loop control system in Fig.4 is used to set a condition for a zero steady-state error providing the following relationship between K_{pc3} and K_{d4}:

$$K_{pc3} = K_{d4} \quad (12)$$

- This reduces the tuning process to only optimizing K_{d3} and K_{d4}. The ITAE performance index.[21] and the MATLAB optimization tool box.[22] are used to assign the tuned 2DOF-3 controller parameters as:

  $K_{pc3} = 228.6328$, $K_{d3} = 1.05229$, $K_{pc4} = 228.6328$, $K_{d4} = 228.6328$ (13)

The step time response of the control system incorporating the 2DOF-3 controller and the type 1 blood glucose process is plotted using the closed-loop transfer function and the controller parameters in Eq.13 and shown in Fig.5.

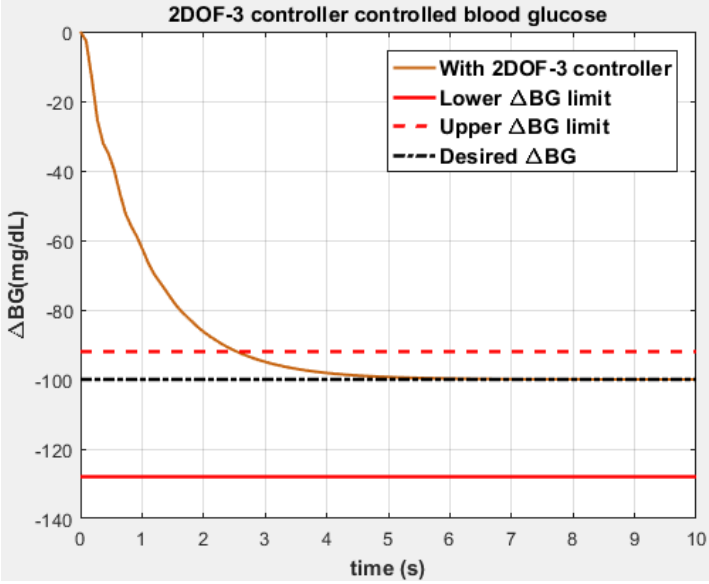

Figure 5: Step time response of the blood glucose using a 2DOF-3 controller.

COMMENTS

The 2DOF-3 controller provided a reference input tracking step time response having the following characteristics:

- Maximum percentage undershoot: zero
- Settling time within ± 2 % tolerance: 3.926 s
- Settling time within ΔLL and ΔUL: 2.500 s
- Steady-state error: zero

Characteristics Comparison of the Four Controllers for Blood Glucose Control

- The time-based characteristics of the control system for the type 1 blood glucose are graphically and quantitatively compared in Fig.6 and Table 1 for reference input tracking.

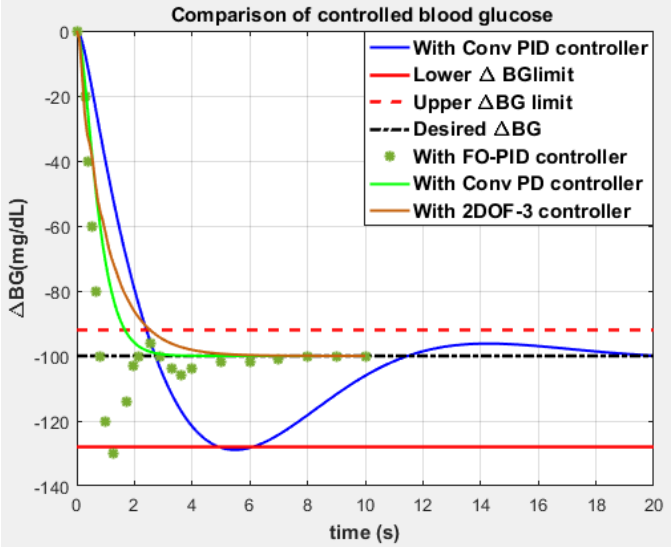

Figure 6: Compared step time response of the blood glucose.

Table 1: Reference input time-based characteristics of the type 1 blood glucose control using PID, FO-PID, PD and 2DOF-3 controllers

Controller	PID	FO-PID	PD	2DOF-3
US_{max} (%)	28.944	30	0	0
T_{s1} (s)	17.235	6	2.333	3.926
T_{s2} (s)	6.100	1.500	1.666	2.500
e_{ss} (mg/dL)	0	0	0	0

US_{max}: maximum undershoot.
T_{s1}: settling time to ± 2% tolerance.
T_{s2}: settling time to normal blood glucose range.
e_{ss}: steady-state error.

CONCLUSION

- The objective of the paper was to investigate the use and tuning of PD and 2FOF-3 controllers to control type 1 blood glucose with comparison with using PID and FO-PID controllers.
- The type 1 blood glucose was an unstable process representing a real challenge for the control system.
- The proposed two controllers were one from the first generation of PID controllers (PD) and the second was from the second generation of PID controllers (2DOF-3) introduced by the author since 2014 onward.

- The two controllers were tuned using different tuning techniques based on zero/pole cancellation, desired closed-loop characteristics of the control system and using the MATLAB optimization toolbox.
- A range of normal blood glucose level was imposed on the step time response for all the investigated controllers to help in selecting the best controller among the four ones.
- The proposed controllers (PD and 2DOF-3) succeeded to eliminate completely the maximum percentage undershoot.
- All the investigated controllers could eliminate completely the steady-state error.
- The proposed PD and 2DOF-3 controllers could generate step time responses with settling time to ± 2 % tolerance of 2.333 and 3.926 s compared with 28.444 s for the PID controller.
- The proposed PD and 2DOF-3 controllers could generate step time responses with settling time to the normal range of blood glucose of 1.666 and 2.50 s compared with 6.10 s for the PID controller.
- The PD controller was chosen as the best controller for the control of type ` blood glucose for its perfect time-based characteristics compared with the other three controllers.

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