Al-Khwarizmi Engineering Journal, Vol. 7, No. 4, PP 54-60 (2011)

Al-Khwarizmi Engineering Journal

Back stepping-Based-PID-Controller Designed for an Artificial Pancreas model

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(Received 2 March 2011; Accepted 20 September 2011)

Abstract

Artificial pancreas is simulated to handle Type I diabetic patients under intensive care by automatically controlling the insulin infusion rate. A Backstepping technique is used to apply the effect of PID controller to blood glucose level since there is no direct relation between insulin infusion (the manipulated variable) and glucose level in Bergman's system model subjected to an oral glucose tolerance test by applying a meal translated into a disturbance. Backstepping technique is usually recommended to stabilize and control the states of Bergman's class of nonlinear systems. The results showed a very satisfactory behavior of glucose deviation to a sudden rise represented by the meal that increase the blood glucose

Keywords:- *Type I diabetes, Backstepping, Bergman's model, oral glucose tolerance test.*

1. Introduction

With more than 246 million affected people worldwide, diabetes mellitus is one of the most widespread diseases and causes 3.8 million deaths per year, similar to HIV/AIDS [1]. Any patient that suffers from diabetes that does properly receives the insulin cure can lead to complications such as nerve damage, brain damage, amputation and eventually death. Diabetes related complications are a worldwide epidemic with high medical, economic and social costs [2]. The normal blood glucose concentration level in the human body varies in a narrow range (70 - 110 mg/dL). If for some reason the human body is unable to control the normal glucose-insulin interaction (e.g. the glucose concentration level is constantly out of the above mentioned range), diabetes is diagnosed. As a result four types of diabetes are known: Type I (also known as insulin-dependent diabetes mellitus), Type II (or insulin- independent diabetes mellitus), gestational diabetes and other special types, like genetic deflections [3].

Type I diabetes mellitus is characterized by theinability of the beta cells of the pancreas islets to produceinsulin, which is essential for the uptake of glucose in themuscles and storage in the liver [1].As known, insulin dosing is divided into two divisions: basal and bolus insulin. The basal insulin is required for fasting conditions; while bolus insulin is calculated to correct for meals or hyperglycemia condition. Both dosages should be adjusted over time. The development of external insulin infusion pumps as well as the introduction of rapid-acting insulin analogues has made automated intensive insulin therapy feasible [4]. Automatic controllers are needed to adjust the insulin therapy according to the measurements of glucose concentrations as illustrated in figure (1). Automatic control of insulin infusion rate especially for type I diabetes proved its ability to give satisfactory results. Different types of automatic controllers are used in the literature. A. Makroglou et al[5] introduced an overview of some of the mathematical models appearing in the literature for use in the glucose-insulin regulatory system in relation to diabetes, enhanced with a

survey on available software. While L. Kovács et al [6] presented a practical method for designing arobust controller to regulate glucose-insulin system for Type 1 diabetic patients under intensive care. Also L. Kovács et al [7] investigated the possibility of using a reduced order estimator for the three-state minimal Bergman model. F. H. El-Khatib et al [8] used an automated adaptive glucose-control system to regulate blood glucose, and showedthe plausibility and practicality of closed-loop blood-glucose control using subcutaneous insulin and glucagon infusion in Type I diabetes. G. Marchetti et al [9] proposed a new glucose control strategy based on a novel combination of insulin boluses for meals and an improved PID control algorithm. H. Kirchsteiger et al [1] showed that it is possible to improve the common treatment of Type I diabetic patients by optimization of the time and quantity of single subcutaneous insulin injections. Y. Wang et al [4] proposed an algorithm can take advantage of frequent glucose measurement to design the basal and bolus insulin simultaneously. Two modern robust control methods are applied by L. Kovács et al [10] the minimal model of Bergman: the disturbance rejection LQ control or minimax control and the robust H∞ control.

In this work back stepping based PID controller analyzed and simulated the three states Bergman model which is the widely used mathematical model due to its simplicity.

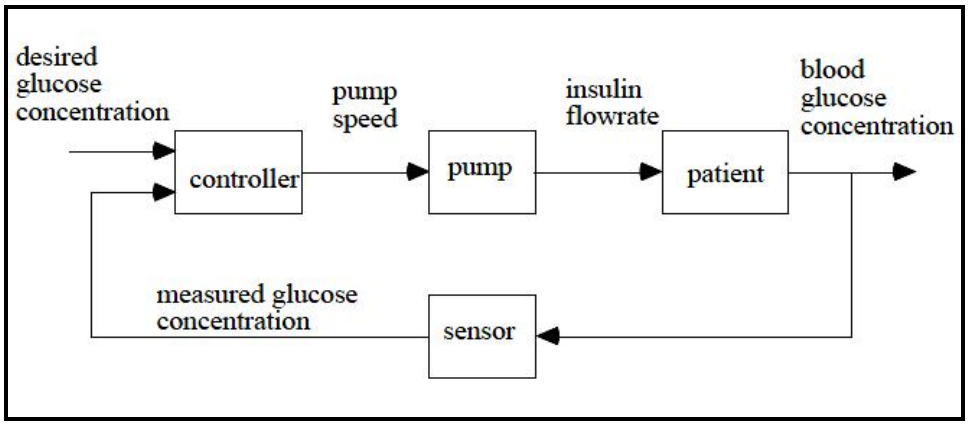

Fig.1. Feedback Control for Blood Glucose.

2. Bergman's system model

Several different models of diabetic systemsexist, for example the very detailed 21th-order metabolic model of Sorensen. However, to have a system that on one hand, can be readily handled from the point of view of control design, but on the other hand represents the biological process properly, the Bergman's three-state minimal patient model is considered.[6,7,10]

$$\dot{G}(t) = -P_1 G(t) - (G(t) + G_B)X(t) + h(t)$$

$$\dot{X}(t) = -P_2 X(t) + P_3 Y(t) \qquad \ldots(1)$$

$$\dot{Y}(t) = -P_4(Y(t) + Y_B) + \frac{i(t)}{V_L}$$

Where $G(t)$ is the plasma glucose concentration above the basal level GB (mg/dL), $X(t)$ (1/min)is remote compartment insulin utilization, $Y(t)$ is the plasma insulin concentration above a basal value *YB* (mU/dL). The control variable is theexogenous insulin infusion rate, $i(t)$ (mU/min), whereas the exogenous glucose infusion rate $h(t)$ (mg/dL min)represents the disturbance.*VL*(dL) representsthe insulin distribution volume and p1, p2, p3, p4 represent the model parameters. As numerical values the authors worked with the numerical values determined by: $p1 = 0.028$, $p2 = 0.025$, $p3 = 0.00013$, $p4 = 5/54$, $GB = 110$, $YB = 1.5$, $VL = 120$[6].In order to linearize the system, its steadystate values are needed: $G0 = X0 = Y0 = 0$, $h0 = 0$, and for $i_0 = p_4 Y_B V_L = 16.667$,The system proved to be stable, controllable and observable [10].

3. Backstepping Based PID Controller

A Backstepping technique is proposed to backbone the design of the PID controller. Backstepping is a technique developed during

1990 by Petar V. Kokotovic and others, for designing stabilizing controls for a special class of nonlinear dynamical. These systems are built from subsystems that radiate out from an irreducible subsystem that can be stabilized using some other method. Because of this recursive structure, the designer can start the design process at the known-stable system and "back out" new controllers that progressively stabilize each outer subsystem. The process terminates when the final external control is reached. Hence, this process is known as backstepping[11].

To apply the Backstepping approach, each of the three equations in (1) is considered separately. Now starting from the first equation: the state is regarded as the plasma glucose deviation $G(t)$ (mg/dL), the virtual input is the remote compartment insulin utilization $X(t)$ (1/min) and the disturbance is the exogenous glucose infusion rate $h(t)$ (mg/dL min). A P controller is designed with X as a virtual input.

The second equation considered which has the remote compartment insulin utilization $X(t)$ as a state variable and the plasma insulin deviation $Y(t)$as the virtual input is considered. The virtual input for the second system will be designed to regulate the error between the remote compartment insulin utilization $X(t)$, the state, and its value as a virtual input X (desired value) in the first equation. Again a P controller for the second virtual input$Y$ is designed.

Finally, the actual controller $i(t)$will be used as a PID controller to regulate the difference between the plasma insulin deviation $Y(t)$and its value as a virtual controller Y as shown in Figure (2). In addition, consider the following:

All the parameters in equation (1) are uncertain but bounded; the disturbance is unknown but a bounded quantity, namely

$$|h(t)| \leq 2 \qquad \ldots(2)$$

and also,

$$(G(t) + G_b) \neq 0\,,\ \forall t \geq 0 \qquad \ldots(3)$$

The two virtual controllers and the actual controller are bounded:

$$X_v = X_v(G) = 0\ at G = 0,$$

$$Y_v = Y_v(X) = 0\ at X = 0 \qquad \ldots(4)$$

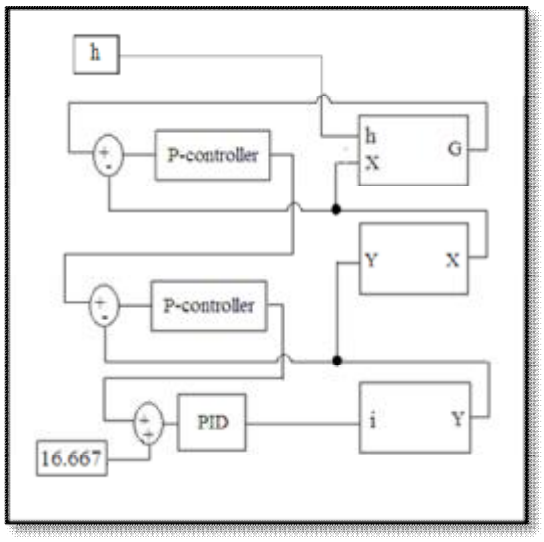

Fig.2.Back Stepping Based PID Approach Used with Bergman's Model.

4. Simulation Results

Bergman's model comes with an artificial pancreas with two inputs: the ingested glucose in plasma after a meal reflected by the disturbance function h(t) and insulin from an external injection *i*(t) that plays the controllers role.

The disturbance function employed here is smooth, continuously differentiable, has zero initial conditions, easily implemented and physiologically accurate function [2]:

$$h(t) = h_m e^{-\alpha(\ln b - c)^2} \qquad \ldots(5)$$

Where $h_m$is the peak value, a, b, c are constants which determine the exact shape.

Figure (3) shows the normal behavior of Bergman's model when exposed to the disturbance which is the oral glucose tolerance test OGTT. There is a monotonic rise in the basal blood sugar by 32 mg/dL until the normal insulin initially existed treats this rise and guide it again to its basal level within$t = 780\ min$. Figure (4) illustrates the disturbance of oral food ingestion model.

The Backstepping approach determines how to stabilize the $G(t)$ subsystem using x, and then proceeds with determining how to derive the real control action on *i* to make the next state y drive x to the control required to stabilize $G(t)$.

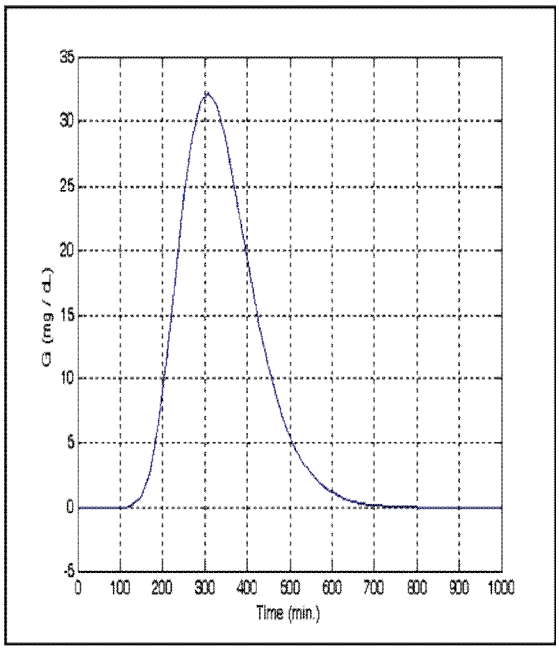

Fig .3. Normal Plasma Glucose Deviation in Response to OGTT.

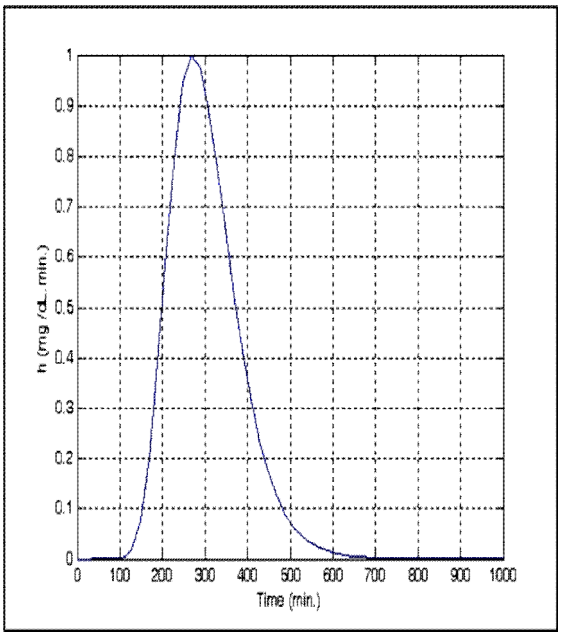

Fig.4. Exogenous Glucose Infusion (OGTT).

Hence there are three control actions to stabilize each state backward. Theactual input signal the *insulin infusion rate* $i(t)$is controlled by PID controller tuned to k_{P3} =0.0627, ki =0.0010, $k_{d=}$ 0.8240 to stabilize the plasma insulin deviation y(t), at this step a P controller is designed with $kp_2 = 25$ to stabilize remote compartment insulin utilization $x(t)$, which finally derives the glucose deviation $G(t)$ to the originusing unity proportional controller ($kp_1 = 1$) when the system issubjected to the meal disturbance illustrated previously; the glucose deviation response of figure (5) is obtained and the basal glucose level is illustrated in figure (6). Figure (7) illustrates the insulin infusion rate while the other systems states are in figures (8, 9).

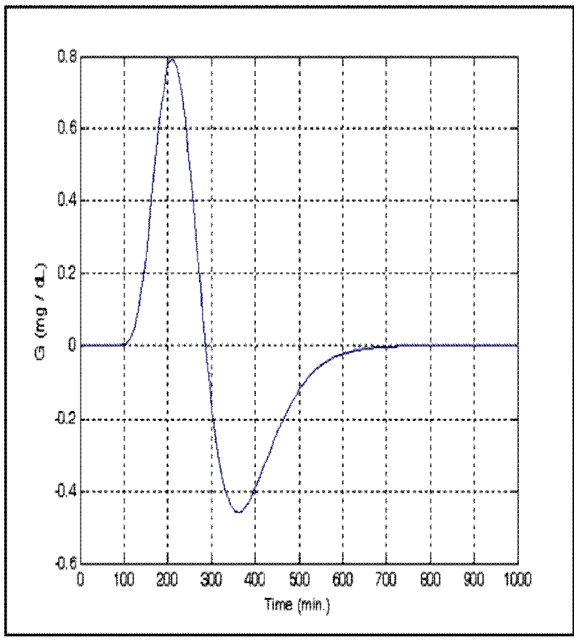

Fig.5. Controlled Plasma Glucose Deviation Using Backstepping Based PID Controller Exposed to OGTT.

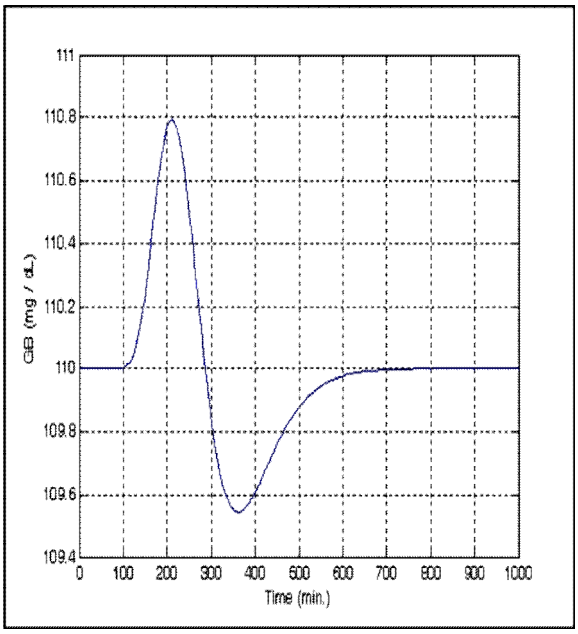

Figure (6): basal glucose level controlled by Backstepping PID.

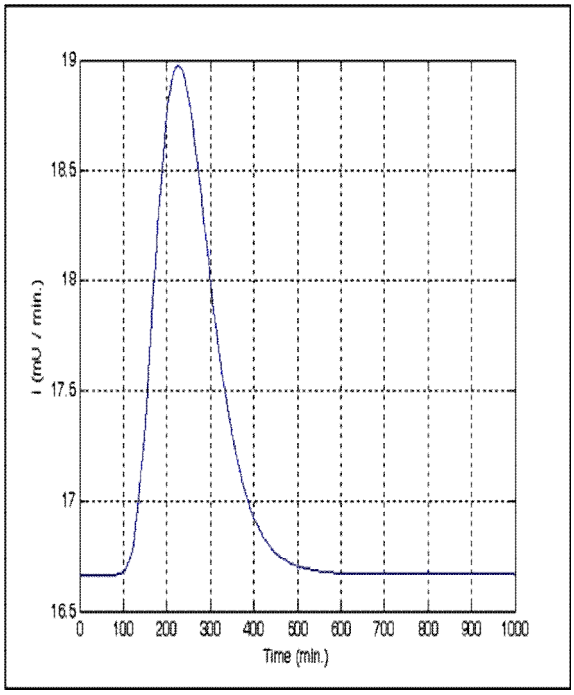

Fig.7. Backstepping PID Controlled Insulin Infusion Rate.

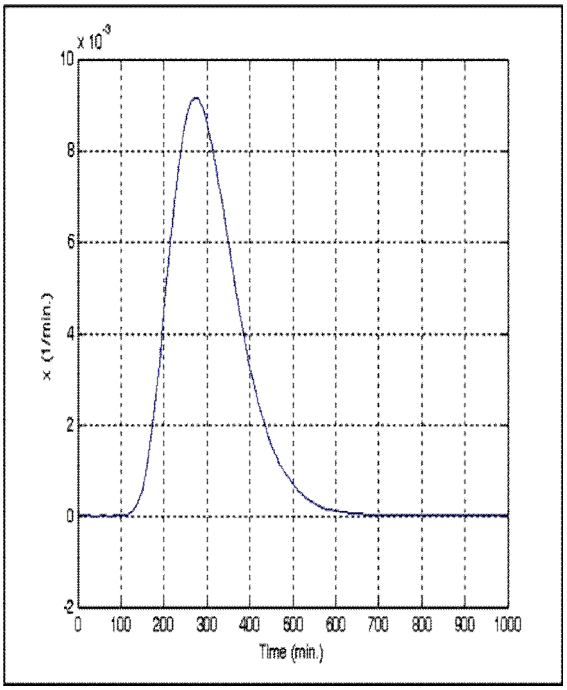

Fig.8. plasma Insulin Utilization Controlled By Backstepping PID.

The Backstepping PID perfectly enhanced the glucose transient response to have a maximum peak of 0.8 mg/dL which is less than 1% of basal level GB=110, also it guided the blood glucose through controlling the insulin infusion rate to the basal level very fast in $t = 570\ min$.

Backstepping technique was very useful to gain this excellent behavior with the three control and stabilizing steps.

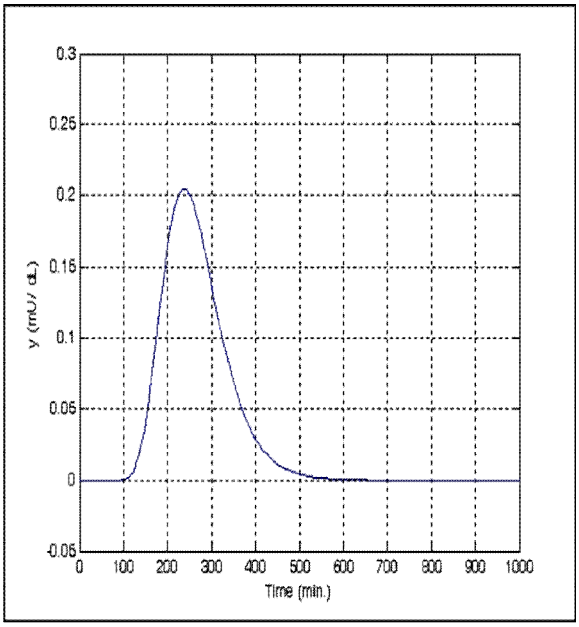

Fig.9. Plasma Insulin Deviation Controlled by Backstepping PID .

These results are compared to those obtained by L. Kovács et al [10] who used modified Minimax, LQ and H controllers to regulate insulin infusion rate as illustrated in table (1).

Table (1)

Controller	Settling time (min.)	Glucose Peak (mg/dL)	Insulin infusion highest level (mU/min.)
Minimax	252	11.7	18.3
LQ	374	24.6	17.5
$H\infty$	456.25	16.5	33.25
Backstepping PID	570	0.8	19

5. Conclusions

Glucose deviation of Bergman's model for artificial pancreas is regulated by designing Backstepping PID controller that directs the insulin infusions rate which stabilize the other two states backward until the glucose deviation is driven to zero after it's excitation by a sudden meal disturbance function that represents the

OGTT. Excellent behavior is obtained on both aspects moderate speed and minimum overshoot. The results are compared to these presented by L. Kovacs. The proposed controller proved a very efficient behavior by giving the lowest glucose deviation peak even less than 1% of the basal level in 213min. Backstepping technique is very much recommended to control such class of nonlinear systems and it is a good base to design any controller like PID that was fairly capable of handling the regulatory problem.

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مسيطر تناسبي-تكاملي-تفاضلي- مستند على الخطوات التراجعية مصمم لنموذج بنكرياس صناعي

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الخلاصة

تم تنفيذ بنكرياس صناعي ليتم معالجة مرضى النوع الاول من مرض السكري تحت الرعاية الخاصه عن طريق السيطرة الاوتوماتيكيه على نسبة ضخ الانسولين. تقنية الخطوات التراجعيه هي التي استخدمت لاضافة تأثير المسيطر التناسبي-التكاملي-التفاضلي على مستوى الجلوكوزفي الدم, بما انه ليس هناك علاقه مباشرة بين المعامل المتغير وهو ضخ الانسولين ونسبة الجلوكوز في الدم في نموذج Bergman والذي تعرض لاختبار تحمل السكر الشفهي بتطبيق وجبة طعام كاضطراب خارجي. تقنية الخطوات التراجعيه هي عادة موصى بها لتحقيق الاستقرار و السيطرة على حالات نمط Bergman من الانظمة اللاخطية.قد اوضحت النتائج تصرف مقنع جدا لاستجابة الجلوكوز لارتفاع مفاجئ ممثل بوجبة والتي تسبب زيادة نسبة الجلوكوزفي الدم.