



Adaptive Integral Backstepping Artificial Pancreas System for Blood Glucose Regulation of Type-1 Diabetic Patients

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ABSTRACT

Diabetes Mellitus (DM) is one of the most prevailing ailments nowadays in our society. It is a metabolic disorder caused by an increase in blood glucose concentration (BGC) above the normal range with the disturbance of starchy foods, fat, and protein metabolism thereby leading to the inability of insulin secretion. An adaptive integral backstepping controller for Artificial Pancreas System (APS) is developed to address the issues of hyperglycemia and hypoglycemia episodes which are two major problems of Blood Glucose Concentration (BGC) control for type-1 diabetes mellitus (T1DM) patients as the current method is manual and based on doctor's advice. Controllers have been designed to automate the regulation process: Proportional Integral Derivative (PID), Fuzzy Logic Controller (FLC), Sliding Mode Controller (SMC), and Integral Backstepping controller (IBC), improved glycemic performance was observed but longer settling of BGC to the basal level. The developed Adaptive Integral Backstepping Control (AIBC) addresses this problem. Firstly, the adaptive parameters of the T1DM patient's model were developed in Simulink. Then the IBC was designed and applied to the developed model to track the basal threshold. The performance metrics of the developed AIBC system were evaluated against settling time, overshoot, and steady-state error. Simulation of AIBC when patient BG level is 230mg/dl obtained a settling time of 9.73 minutes while both controllers achieved 0% overshoot and 0 steady-state error, a 15.39% settling time improvement compared to IBC. The implication of the developed AIBC is fast steady-state tracking and better settling time, implying quick recovery of patients from hyperglycemia. Also, an impulse signal was applied to the controller (25mg/dl and 45mg/dl with a duration of 4 minutes and 8.2 minutes) which shows glucose intake by the patient as a disturbance to the system at 500 minutes, when glucose intake was 25mg/dl, patient's model was restored to steady state using AIBC and IBC at 540 minutes and 565 minutes respectively, while at 45mg/dl it was restored at 578.2 minutes and 590.4 minutes for AIBC and IBC respectively, showing the superiority of developed controller.

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INTRODUCTION:

Diabetes Mellitus (DM) is viewed as one of the most well-known widespread diseases in the world (Lunze *et al.*, 2013). It can be defined as a metabolic disease accompanied by

failure of the pancreatic cells to regulate the blood sugar (glycemic) level in accordance with the desired range of 70-180 mg /dl (Abu-Rmileh *et al.*, 2010). It is associated with symptoms like excessive urination, tiredness, thirst, hunger, and

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weight loss (Saleem *et al.*, 2017). Type 1 Diabetes Mellitus (T1DM), Type-2 Diabetes Mellitus (T2DM), and Gestational Diabetes Mellitus (GDM) (Thupili & Srinivasan, 2009) are the classifications of diabetes mellitus. Type 1 diabetes mellitus (T1DM) also called insulin-dependent diabetes mellitus occurs because of a deficiency of insulin caused by autoimmune system damage to the insulin-producing beta cells within the pancreatic cell. The T1DM is accompanied by the inability of the human body to produce its own supply of insulin due to the body's inability to stabilize blood glucose within the normal range (70-180 mg/dl) thereby leading to chronic hyperglycemia that is high Blood Glucose Concentration (BGC) above 180mg/dl (BGC > 180mg/dl) leading to health complications such as blindness, kidney failure, and hearth failure. On the other hand, hypoglycemia (BGC < 70mg/dl) can also result in coma or even death of a patient. Hence, regular exogenous insulin therapy is needed to improve the quality of life for T1DM patients. This is to ensure tight glycemic control within the normal range of blood glucose regulation and to prevent long-term complications (Melling *et al.*, 2013; Nath *et al.*, 2019).

The present medication for the treatment of T1DM patients requires 3-5 daily insulin injections or more times per day or continuous insulin administration with a manually controlled external pump (León-Vargas *et al.*, 2015) Notwithstanding these conditions, there is the likelihood of the patient to experience hypoglycemic episode. This is primarily owing to non-optimal decisions when manually controlling insulin delivery (open loop blood glucose regulation). To abate, patients predetermining each insulin dose manually (open loop) and to hinder the large fluctuations in blood glucose concentration, an Artificial Pancreas System (APS) which is also known as "closed loop blood glucose regulation" has been developed to overcome the drawbacks of conventional therapies. The system comprises a Continuous Glucose Monitoring (CGM) system, controller and Blood Glucose (BG) sensor. The basic ideas of the APS (closed loop blood glucose regulation)

is to compute the desired insulin dosage using a control algorithm based on continuous glucose measurements which are acquired through a sensor without human input (León-Vargas *et al.*, 2015; Lunze *et al.*, 2013).

Various technique has been proposed to improve the glycemic performance of a T1DM patients using different control techniques such as PID, SMC, IBC, and Robust controllers for the APS have been investigated in the blood glucose regulation, these controllers automatically control the blood glucose level of patients to a various degree. The ability of the controllers to restore the blood glucose level of the diabetic patients to normal level remains a key issue, since the settling time reported are not short enough. Hence, there is need to develop a controller with an adaptive parameter to achieve an improvement in glycemic performance due to nature of biological system.

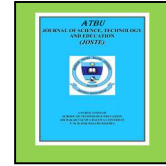
In this research, an Adaptive Integral Backstepping Control (AIBC) technique was designed to improve the glycemic control of T1DM patients. To achieve the adaptiveness of the controller, the insulin action parameter of the patient's model was made adaptive using the Lyapunov rule of adaptive control and the Simulink model was implemented. Metrics of evaluation of the developed works was using overshoot, settling time and steady state error and compared with the work of Babar *et al.*, (2019). Also, a Graphical User Interface (GUI) was developed for an artificial pancreas system to display different BG levels. Thus, the significance of this work is the development of an adaptive integral backstepping controller for APS to the health management system in addressing the issues of hyperglycemia and hypoglycemia episode. The remainder of this work is structured as follows: section one highlights the background to the study. Section two is the literature review of relevant work and pertinent fundamental concepts related to the work. Section three describes the material used and the design methodology employed in carrying out the work. Final Section presents the results and discussion based on the findings and recommendations.

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LITERATURE REVIEW

This section explains some basic concept related to this work.

Overview of Diabetes mellitus

Diabetics is among the major cause of death. It a state of abnormal health where the human system either produces little or fail to produce hormone or the body immune system becomes gradually resistant to human action (Haidar *et al.*, 2016). The rise in the blood sugar concentration of the patient with diabetes above the renal threshold (180mg/dl). Based on these there are three characteristics of diabetics mellitus: normoglycemia, hyperglycemia and hypoglycemia (Haidar *et al.*, 2016). In the normoglycemia the BGC is within normal range (70-180) mg/dl, in hyperglycemia, blood glucose (BG) level is beyond 180mg/dl, hypoglycemia or low BGC which occur when BG level reaches below 70mg/dl. Both hyperglycemia and hypoglycemia are dangerous and could result in fatality if the patient is not given quick attention.

There are three types of diabetes known namely: gestational, Type II and Type I diabetic mellitus. Gestational diabetics is mostly observed in pregnant women, it manifest due to glucose intolerance in the body It is first been diagnosed during gestation (Melling *et al.*, 2013).mothers that are diagnosed with this have a tendency of having Type 2 diabetics. This type of diabetics have some risk association to both mother and child, high birth weight, skeletal muscle malformation and increase in fetal insulin level thereby leading to respiratory distress syndrome (Afrand *et al.*, 2012).treatment include exercise, proper diet and medication and weight loss(Haidar *et al.*, 2016; Stage *et al.*, 2003). The

type II diabetics also called insulin independent diabetics is due to insulin resistance or reduction in the insulin sensitivity in the peripheral's tissues, leading to inadequate insulin production by beta cells (Reddy & Srinivasan, 2009). Health factors such as obesity, physical inactivity, family ancestry of diabetes and sedentary lifestyle are causes and treatment are proper medication and weight reduction. The Type I diabetics also known as insulin dependent is common within the adolescent individuals and is inherited from the parents (Patel *et al.*, 2012; Pietropaolo & Le Roith, 2001). It is due to loss of insulin producing beta cells due to destruction of autoimmune reaction thereby resulting in absolute insulin deficiency(Cooke & Plotnick, 2008), general symptoms of T1DM include frequent urination, increased thirst, increased hunger and weight loss (Umapathy, 2011).Patient need to be totally placed on exogenous administration of insulin (external insulin) in order to maintain the body glycemc control within the normoglycemic state (Butt *et al.*, 2019; Boiroux *et al.*, 2018).

Glucose regulation in the human body

The human assimilation procedure is portrayed as: when an individual eats food, starches in the food get converted to glucose to produce energy in the body. This glucose is discharged in the circulatory system and the blood glucose level rises. This upsurge is detected by beta-cells in pancreas that discharges insulin to aid up-take of glucose by cells in the body to convert it into energy. Insulin also assists in storing additional glucose in liver as glycogen. This returns BGC to normoglycemic state (Butt *et al.*, 2019). This is shown in Figure 1.

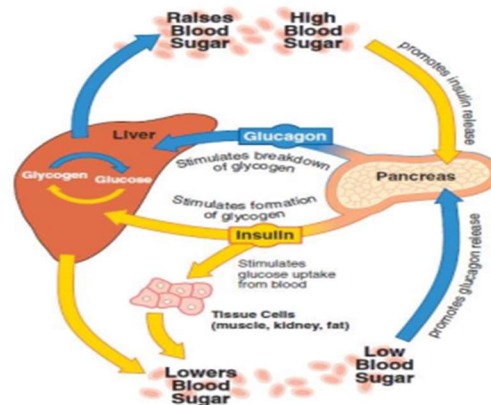


Figure 1: Glucose Regulation in Human Body (Babar *et al.*, 2019)

During exercise and other strenuous activities, the BGC in the body may fall below the threshold. The secretion of a hormone called glucagon from alpha-cells in the pancreas follows immediately after this, so as to stimulate the liver to produce glucose by the process known as glycogenolysis, thereby raising the blood glucose concentration (Butt *et al.*, 2019).

Artificial pancreatic system

The Artificial Pancreas system (APS), is also called a closed loop blood glucose

regulator for diabetic patient. It is an arrangement of components (system) that autonomously adjust patient's insulin infusion rate so as to conserve his/her blood sugar in accordance the predefined range. It comprises of a glucose sensor, insulin infusion pump device and control algorithm that computes the insulin dosage (Cobelli *et al.*, 2011; Colmegna *et al.*, 2018). The artificial pancreas system (APS) diagram is depicted in the Figure 2.2.

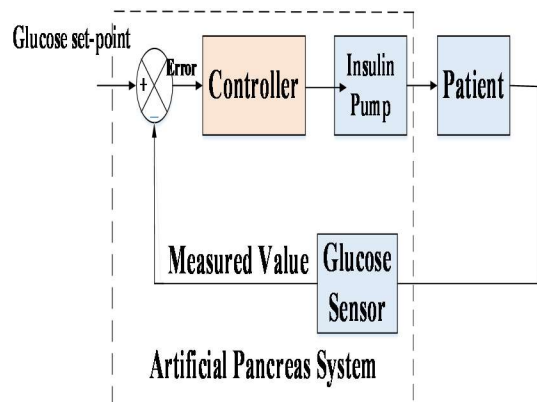


Figure 2: Block diagram of APS (Butt *et al.*, 2019)

From Figure 2, the blood glucose sensor is utilized to obtain the glycemic content in human's body and this measured value is now compared with the required amount of blood

sugar. The error which is the difference between the desired estimated value and measured value is inputted into the controller which now output the control signal needed to the error to zero.

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APS can be classified into two types; dual hormone APS and single hormone APS (Butt et al., 2019). The Dual hormone APS also known as bi-hormonal or insulin and glucagon APS. This APS delivered glucagon in conjunction with insulin. Adding a glucagon as a second hormone increase the complexity of the system (Butt et al., 2019), this type of APS is prone to the risk of hypoglycemia should the glucagon-infusion catheter fail due to increase doses of insulin (Haidar et al., 2016). In the Single Hormone APS also known as insulin delivery APS. This type of APS was developed in order to replicate the function of beta-pancreatic cells (Butt et al., 2019). This research will employ the use of single hormone APS for its implementation.

Components of artificial pancreas systems.

There are three components of artificial pancreatic systems. These are; Continuous Glucose Monitoring Sensor (CGM) or blood glucose monitor (sensor), Insulin Infusion Pump (actuator) and Controller (Carrasco et al., 2014).

- i. Continuous Glucose Monitoring sensor (CGM): This is an electrochemical device that uses a subcutaneous electrode to measure blood glucose concentration in the interstitial fluid (Kumareswaran et al., 2009).
- ii. Insulin Pump (Actuator): This is a medical device that is used for continuous subcutaneous injection of insulin treatment into the T1DM patients (Kumareswaran et al., 2009).
- iii. Control Algorithm: A piece of code developed for BG regulation (Kumareswaran et al., 2009).

Mathematical model of T1DM patients

The modified version of Bergman's minimal model known as extended Bergman's minimal model (EBMM) has been used to represent the glucose-insulin regulatory system of type 1 diabetes mellitus (T1DM) patients. It is an important compartmental model comprises of plasma glucose compartment, remote insulin compartment, plasma insulin compartment and meal disturbance dynamics as the fourth state of

the state-space model (Nath et al., 2018). But for the purpose of this research, the mathematical model reported in the work of (Babar et al., 2019) would be considered. The mathematical model is presented as follows.

$$\frac{dy_1}{dt} = -m_1(y_1 - G_b) - y_1y_2 + y_4 \quad (1)$$

$$\frac{dy_2}{dt} = -m_2y_2 + m_3(y_3 - I_b) \quad (2)$$

$$\frac{dy_3}{dt} = -m_4(y_3 - I_b) + u_t \quad (3)$$

$$\frac{dy_4}{dt} = -m_5y_4 \quad (4)$$

Where: $y_1(t)$ is Plasma glucose concentration in mg/dl , $y_2(t)$ is the remote insulin in (min^{-1}) , $y_3(t)$ is the insulin concentration in mU/l , $y_4(t)$ is the fisher's meal disturbance in $(mg/dl/min)$, $u(t)$ is the external glucose input in $(\mu MolL^{-2}min^{-1})$, $G_b(t)$ is the basal plasma glucose in $mMolL^{-1}$, $I_b(t)$ is the basal plasma Insulin in (mUL^{-1}) , $n(t)$ is the fractional disappearance rate in (min^{-1}) , m_1 is the glucose effectiveness factor in (min^{-1}) , m_2 is the delay in insulin action in (min^{-1}) , m_3 is the patient parameter in (min^{-1}) and m_4 is the insulin degradation rate in (min^{-1}) , m_5 is the meal disturbance in (min^{-1}) .

Backstepping controller technique

For a nonlinear system, the stability of the system within the equilibrium position can be demonstrated by finding an appropriate Lyapunov function. The Lyapunov stability criteria has been used to carry out controller design through Lyapunov function. The technique employed to develop a control force is backstepping. Backstepping control technique is one of the nonlinear control techniques that is optimally applied on a system containing controllable subsystems and it is based on Lyapunov function. It is a method for providing a repeated (recursive) technique of designing control law for systems that are nonlinear in an adaptable strict-feedback form (Amiri et al., 2013). In backstepping control design, the nonlinear system or subsystem is given by:

$$\dot{a} = f(a) + g(a)u(t) \quad (5)$$

$$p = h(a) \quad (6)$$

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Where state vector is denoted by a , p represents output of the system and the control law is denoted by $u(t)$. The control input is develop in order to reduce the insulin concentration with the help of insulin pump (Butt *et al.*, 2019). For the purpose of this study, the

$$z_1 = y_1 - y_{1ref} \quad (7)$$

The goal is to converge the error signal z_1 to zero. By taking the derivative of equation 7 and putting equation 1 into equation 7, we have:

$$\dot{z}_1 = -m_1(y_1 - G_b) - y_1 y_2 + y_4 - \dot{y}_{1ref} \quad (8)$$

By introducing an integral term k_1 for fast convergence of the states to the reference value as:

$$k_1 = \int (y_1 - y_{1r}) \quad (9)$$

By considering a Lyapunov candidate function for the system as:

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} k_1^2 \quad (10)$$

By differentiating equation (10) with respect to time, we get:

$$\dot{V}_1 = z_1 \dot{z}_1 + k_1 \dot{k}_1 \quad (11)$$

By introducing the second error as:

$$z_2 = y_2 - a_2 \quad (12)$$

$$y_2 = z_2 + a_2 \quad (13)$$

By substituting equation (13) into equation (8), we get:

$$z_1 = -m_1(y_1 + G_b)y_1(z_2 + a_2) + y_4 - \dot{y}_{1re} \quad (14)$$

Similarly, by substituting equation (13) and (8) into equation (11)

$$\dot{V}_1 = z_1(-m_1(y_1 - G_b) - y_1(z_2 + a_2) + y_4 - \dot{y}_{1ref} + k_1) \quad (15)$$

The virtual control input a_2 must ensure \dot{V}_1 to be negative definite.

$$-m_1(y_1 - G_b) - y_1(z_2 + a_2) + y_4 - \dot{y}_{1ref} + k_1 = s_1 z_1$$

Where s_1 is a positive definite and solving for a_2 we have

$$a_2 = \frac{1}{(y_1)} (-m(y_1 - G_b) - y_1 z_2 + y_4 - \dot{y}_{1ref} + k_1 + s_1 z_1) \quad (16)$$

By putting the value of equation (15) into (14) we have:

$$V_1 = -k_1 z_1^2 - z_1 z_2 y_1 \quad (17)$$

The Lyapunov candidate function for the next virtual control input is given by

$$V_2 = V_1 + \frac{1}{2} z_2^2 + \frac{1}{2} k_2^2 \quad (18)$$

By taking the derivative of the above equation:

$$\dot{V}_2 = \dot{V}_1 + z_2 \dot{z}_2 + k_2 \dot{k}_2 \quad (19)$$

$$\dot{V}_2 = -s_1 z_1^2 + z_2(-m_2 y_2 + m_3(z_3 + a_3 - I_b) - \dot{a}_2 - z_1 y_1 + k_2)$$

The virtual control law a_3 is given by:

$$a_3 = \frac{1}{m_3} (-s_2 z_2 + m_2 y_2 + m_3 y_3 + m_3 I_b - \dot{a}_2 + -k_2) \quad (20)$$

The third error is given by:

$$z_3 = y_3 - a_3 \quad (21)$$

By taking the time derivative of equation (21) and substitute equation (3), we have:

$$\dot{z}_3 = \dot{y}_3 - \dot{a}_3 = -m_4(y_3 - I_b) + u \quad (22)$$

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Similarly, by using Lyapunov candidate for obtaining control law so that the three errors z_1, z_2 and z_3 should converge to zero, y_1 tracks y_{1ref} , y_2 track a_2 and y_3 track a_3 as

$$V_3 = V_2 + \frac{1}{2} z_3^2 \quad (23)$$

Taking time derivative of equation (23) and substituting equations (19) and (22), we have:

$$\dot{V}_3 = -s_1 z_1^2 - s_2 z_2^2 + z_3(z_2 m_3 - m_4(y_3 - I_b) + u - \dot{a}_3) \quad (24)$$

The control law is obtained as:

$$u = -s_3 z_3 - z_2 m_3 + m_4(y_3 - I_b) + \dot{a}_3 \quad (25)$$

Performance metrics

Performance metrics are metrics used to determine the performance improvement, effectiveness, efficiency, and appropriate levels of internal controls of a system (Alagoz *et al.*, 2015). Amongst the performance metrics to be considered in this work are the transient response and the steady state response.

Transient Response

This is one of the time responses of a control system. It is response of the system that goes from the initial state to final state until the system becomes. The main parameters of the transient response of the system are: settling time, overshoot (Ogata, 2010).

- i. **Settling time:** This one of the time specifications of the transient state. It is the time required for the response to reach the steady state and stay within a specified tolerance bands around the final value. In general, the tolerance band be 2% or 5%.
- ii. **Overshoot:** This is also one of the time specifications in a control system. It is the deviation of the response at peak time from the final value response.

Steady state response

This is also one of the parameters used for measuring the relative stability of the system. It is the response of the system after it has finally settled.

- i. **Steady state error (SSE):** The transient response of a practical control system often exhibits damped oscillation before reaching a steady state. If the output of the system at the steady state does not exactly agree with the input, such system is said to have steady state error. It is the value of error signal when time $t \rightarrow \infty$. The SSE

is the measured of system accuracy (Alphinas *et al.*, 2017).

RELATED WORKS

Numerous studies have been proposed in this context for example, Goharimanesh *et al.*, (2014), Hu & Li (2015), Mahmud *et al.*, (2017) used a heuristics tuned proportional, integral and derivative(PID) scheme for selection of optimal PID parameters aimed at improving settling time, overshoot and steady state error(SSE).Backstepping Sliding Mode Controller (BSMC) control technique was used in Parsa *et al.*, (2014), Sylvester & Munje (2017), Munir *et al.*, (2016).Bergman minimal model was used to develop the backstepping sliding mode nonlinear control technique so as to track the required blood concentration. Ahmad *et al.*, (2017) designed an APS for T1DM based on super twisting Sliding Mode Controller (SMC) to control blood sugar level. The switching control force for the super twisting control algorithm was intended for reduced chattering effect of conventional SMC design. Comparison of result was carried out with conventional SMC in terms of settling time, overshoot and steady state error (SSE). Result shows superiority of super twisting SMC over conventional SMC in terms of overshoot and steady state error although no convergence of BG to the basal level during hyperglycemic situation. Alam *et al.*, (2018) used super twisting SMC augmented with fuzzy technique, Bergman minimal model (BMM) was used for design of controller to study dynamic behavior of glucose and insulin in the body. Simulation result was compared super twisting SMC using transient response and steady state response and steady state response, proposed scheme show improvement in settling time, overshoot and

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steady state error compared to work of Ahmad et al., (2017), although chattering was observed there is need to reduce its effect to shorten the glucose settling time, improvement reported on settling time is insignificant. Singh *et al.*, (2018), designed an optimal based PID control scheme, BMM model was used for glucose-insulin regulatory analysis, proposed scheme was simulated in MATLAB and performance compared with the controllers reported in previous works using settling time overshoot and steady state error as performance metric, result indicate ACO tuned PID shows superiority over previous work. However, there was a high overshoot reported in their work which will endanger the health condition of the patient. Ahmad et al., (2019) developed an adaptive backstepping control scheme for an APS was designed for T1DM patients. In the work, the BMM model was used to carry out the controller design for T1DM patient. The control scheme was simulated and comparative study was carried out between the performance of the proposed controller, Fuzzy Proportional Integral (Fuzzy-PI) and Genetic fuzzy-PI controller in terms of settling time, overshoot and steady state error.

The results obtained shows that, the proposed controller demonstrated superiority in terms of settling time and overshoot over the works considered. However, these improvements were at huge expense of steady state error which will inevitably leads to instability in the tracking of the basal level. Babar *et al.*, (2019), work on the artificial pancreas for the regulation of blood sugar concentration in T1DM patients using Integral Backstepping controller (IBC). In the proposed work, extended Bergman's minimal model (EBMM) was used to carry out the controller designed. In the work, an IBC, Backstepping control (BC) scheme and Fuzzy Logic Control (FLC) technique were used for blood glucose stabilization in T1DM. The stability of both IBC and backstepping controller were carried out using Lyapunov stability theorem. Also, blood sugar concentration and internal insulin level are the inputs while insulin dose is the output of FLC and Gaussian membership

function was adopted in their work. Simulation performed in MATLAB was compares with FLC and PID controllers using settling time, overshoots and steady state error as performance matrices. The proposed controller exhibited a better performance compared to conventional PID and FLC. Paiva et al., (2020) designed a Fractional order Proportional Integral Derivative (FOPID) controller of artificial pancreas for controlling the blood sugar concentration for T1DM patient. Dalla man patient model which comprises of glucose subsystem, insulin subsystem, gastrointestinal subsystem, liver subsystem, kidney subsystem was used for the design of the proposed controller. Also, Nelder-Mead optimization algorithm was used to tune the parameters of the FOPID. The developed control methodology was simulated in MATLAB/Simulink, transient analysis was carried out and the result is compared to that of standard (PID) scheme, where the proposed controller showed better improvement in terms of overshoot and steady state error. However, the improvement of the blood glucose regulation was at the expense of longer settling time. Dubey et al., (2021) developed a proportional integral derivative PID controller with MATLAB/Simulink for the control of blood glucose level of T1DM patient. The insulin delivery system comprises of glucose sensor, a controller and insulin pump. The optimal parameters of the controller was obtained using tuning methods such as: Process Reaction Curve tuning process, Ziegler-Nichols (Z-N) rule, Approximate constrained Integral gain optimization (AMIGO) and Chien-Hrones Reswick (CHR). The developed controller was implemented on a model of the T1DM patient which was modelled based on dynamics behavior of the patient. Simulation performance comparison of the developed controllers (ZN-PID, CHR-PID and AMIGO-PID) was evaluated using settling time, overshoot and steady state error.

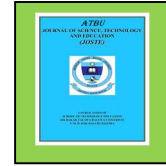
Result shows that all the three controllers attained stability with respect to steady state error while ZN-PID and AMIGO-PID exhibited high overshoot and longer settling time.

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However, there is need to further improve on this results as high overshoot and longer settling time which affect the performance of the system. Khaqan et al., (2022) developed control techniques for the glycemic control of T1DM patients. Here the mathematical models which comprise of glucose insulin dynamic was obtained based on experimental data. Discrete transfer function was obtained from the developed mathematical model and then transformed into continuous domain by zero order hold. Two linear control techniques such as (PID and LQR) and nonlinear control such as (SMC and variant SMC) was studied and implemented on glucose insulin system models for continuous glucose monitoring. Simulation and performance comparison was carried out to investigate the performance of the developed (PID, LQR and SMC) controllers using settling time, overshoot and steady state error as the performance metrics. The simulation results showed that SMC controller obtained better results in terms of tracking the desired glucose level (80mg/dl). The results obtained from conventional SMC was further compared with another variant of SMC controller which is based on linear transformation. The results revealed better performance in terms of overshoot and steady state error. However, chattering in the control input resulted due to switching action, which is quite evident from the presented simulation results. Ronald et al., (2023) presented a novel application of PSO for optimal

MATERIALS AND METHODS

This section present materials and methods used for the development and simulation of the Artificial Pancreas System (APS). The material used includes a desktop computer with its specification stated in Table 1 below, and MATLAB R2019b software, for simulating the developed Adaptive Integral Backstepping Controller (AIBC) with the Type 1 Diabetes Mellitus (T1DM) patient's model. The Method highlight step-by-step process leading to the implementation of the stated objectives based on the following

tuning of PID controller for high performance APS for T1DM patient. In their work, the Simulink model of the patient was designed based on the linearized BMM. The objective function was formulated based on the controller gains and the PSO was used for the optimal tuning of the gains parameter. The developed control methodology was simulated, transient analysis was carried out and the result is compared to that of PID and input/output feedback linearization) where the proposed controller showed better performance in terms of steady state error. However, there was a high overshoot and longer settling time which is not good to the system in terms of practical application. Hence, the need for further improvement. It is evident that the blood glucose concentration control for a T1DM patients have been given a significant research attention leading to the development of different controllers used for APS such as PID, IBC, LQR, FLC and SMC controllers. Most of the works done tried to focus on solving either the problem of higher overshoot or steady state error. However, the effect of longer settling time required for glucose to reach the desired level has not been properly addressed as this frequently results in diabetic patients remaining in hyperglycemia for an appreciable duration of time before they are restored to normalcy. Therefore, developing an adaptive integral backstepping controller with an improved glucose settling time for the control of BGC for T1DM patients is the basis for which this research is inspired.

Development of the AIBC technique with the T1DM patient model

The mathematical model of the system was first obtained from the work of (Babar et al., 2019). The adaptive parameters of the system were modelled using Lyapunov rule of adaptive control and then an Integral Backstepping Control (IBC) was developed. The developed control scheme is expected to regulate the BGC within the pre-defined range.

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Design of the adaptive parameters based on Lyapunov rule using reference adaptive control.

The adaptation laws can easily be design by first defining the suitable Lyapunov candidate function V as:

$$V = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 + \frac{1}{2\gamma_1} \tilde{m}_1 \dot{\tilde{m}}_1 + \frac{1}{2\gamma_2} \tilde{m}_2 \dot{\tilde{m}}_2 \quad (26)$$

Where: γ_1 and γ_2 are the adaptive gains

The derivative of the Lyapunov candidate function can be express as:

$$\dot{V} = z_1 \dot{z}_1 + z_2 \dot{z}_2 + \frac{1}{\gamma_1} \tilde{m}_1 \dot{\tilde{m}}_1 + \frac{1}{\gamma_2} \tilde{m}_2 \dot{\tilde{m}}_2 \quad (27)$$

$$\dot{V} = -k_1 z_1 + \tilde{m}_1 \left[(y_1 - G_b) z_1 + \frac{1}{\gamma_1} \dot{\tilde{m}}_1 \right] + \tilde{m}_2 \left[y_2 z_2 + \frac{1}{\gamma_2} \dot{\tilde{m}}_2 \right] \quad (28)$$

To make $\dot{V} \leq 0$, the simplest way is to make the items in a square bracket equal to zero thereby obtaining the parameters adaptation laws

$$\tilde{m}_1 \left[(y_1 - G_b) z_1 + \frac{1}{\gamma_1} \dot{\tilde{m}}_1 \right] = 0$$

By removing the square brackets

$$\frac{1}{\gamma_1} \dot{\tilde{m}}_1 + (y_1 - G_b) z_1 = 0$$

Therefore, the adaptation law is derived as:

$$\dot{\tilde{m}}_1 = -\gamma_1 (y_1 - G_b) z_1 \quad (29)$$

Similarly, for \tilde{m}_2

$$\tilde{m}_2 \left[y_2 z_2 + \frac{1}{\gamma_2} \dot{\tilde{m}}_2 \right] = 0$$

By removing the square bracket and simplifying for $\dot{\tilde{m}}_2$

$$\frac{1}{\gamma_2} \dot{\tilde{m}}_2 = -y_2 z_2$$

$$\dot{\tilde{m}}_2 = -\gamma_2 y_2 z_2 \quad (30)$$

Where \tilde{m}_1 and \tilde{m}_2 are the glucose effectiveness factor and insulin action parameter.

γ_1 and γ_2 are the adaptive gains.

To develop the Simulink model of the adaptive parameter, the mathematical model of the adaptive parameters presented in equations

(29) and (30) were used. The Simulink model of the adaptive parameters is presented in Figure 3

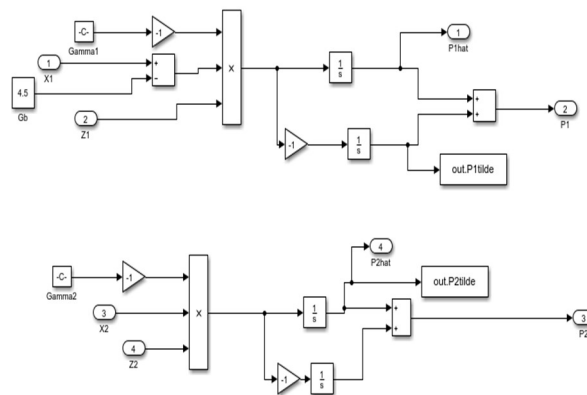


Figure 3: Simulink model of the adaptive parameter

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The Simulink model of the adaptive parameter in Figure 3 is made up of gains, constant blocks, input ports, and output ports that represents system outputs. The parameters used

in simulating the type 1 diabetes mellitus patient model was adopted from (Babar *et al.*, 2019) and are presented in Table 1.

Table 1: T1DM Patients Model Parameters (Babar *et al.*, 2019)

Parameters	Values	Unit
Basal Plasma Glucose (G_b)	4.5	$mMolL^{-1}$
External Glucose Input (dt)	0.00769	$\mu ML^{-2} min^{-1}$
Glucose Effective Factor (m_1)	0	min^{-1}
Delay in Insulin Action (m_2)	0.025	min^{-1}
Patient Parameter (m_3)	0.000013	$mUL^{-1} min^{-2}$
Insulin Degradation Rate (m_4)	0.021	min^{-1}
Meal Disturbance (m_5)	0.05	min^{-1}
Basal Plasma Insulin (I_b)	4.5	mUL^{-1}
Fractional Disappearance Rate of Insulin	0.09259	min^{-1}

Development of the Simulink model of the T1DM patient

The mathematical model of the T1DM patient presented in equations (1) to (4) in chapter two was modelled in Simulink to obtain the system's output X1, X2, X3, and X4 which respectively represent blood glucose concentration, remote insulin concentration,

plasma insulin concentration, and meal disturbance. The resulting Simulink model of the T1DM patient is presented in Figure 5.

It can be seen from Figure 4 that the system takes in two inputs (basal plasma glucose and basal plasma insulin) which represent the desired output of the patient's model and generates four outputs (X1, X2, X3, and X4).

Table 2: The designed performance specification for the T1DM patient

Performance Specification	Design Specification
Settling Time (minutes)	Less than 15minutes
Overshoot (%)	0
Steady State Error	0

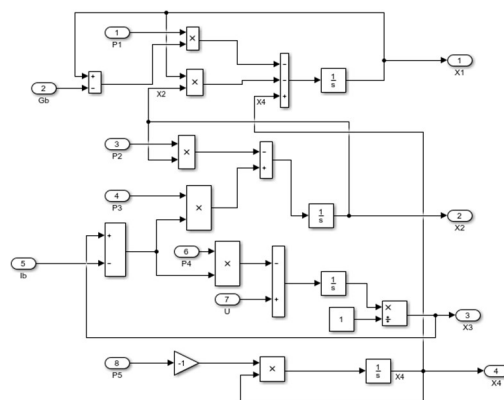


Figure 4: Simulink Model of the T1DM Patient.

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Development of adaptive integral backstepping controller (AIBC) with T1DM patient.

The adaptive integral backstepping controller was developed to track the BGL within the predefined range. The control law for IBC

was designed in Simulink using equation (25) while the virtual stabilization was designed based on equations (16) and (20). The error equations (12) and (21) were used in modeling the error subsystem. The complete model of the AIBC control system is presented in Figure 6.

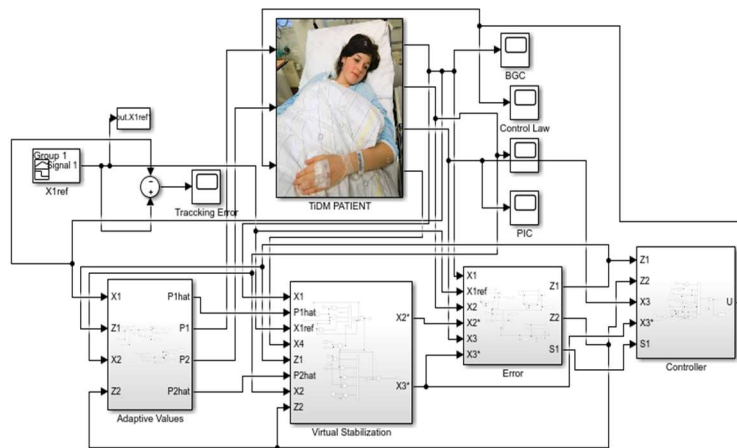


Figure 5: Simulink Model of AIBC Controller

Figure 5 showed the developed Simulink model of the AIBC based T1DM patient. The model made up of five subsystem blocks: the T1DM patient model, adaptive parameters, virtual stabilization, error and controller. The desired reference i.e., the basal value (80mg/dl) was generated using signal builder block. The

response of the states of the system was generated using scope blocks.

The initial conditions reported in the work of Nath et al., (2018) were adopted and presented in Table 4 for the simulation of the system.

Table 3: T1DM Patient's Initial Conditions

Parameters	Units	Initial Condition
X1	mg/dl	230
X2	min ⁻¹	0
X3	mUI ⁻¹	7
X4	mgdl ⁻¹ min ⁻¹	10

Performance evaluation

To evaluate the performance of the developed AIBC controller, the work of Babar et

al., (2019) that uses the IBC based controller was replicated in Simulink and the resulting model is presented in Figure 6:

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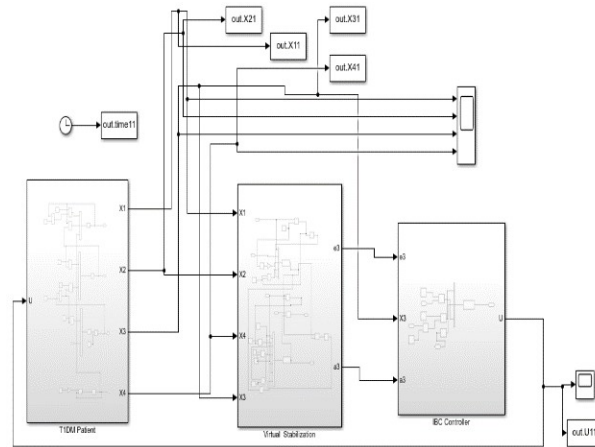


Figure 6: IBC Control System Model

Figure 6 showed the replicated Simulink model of IBC control system model. The model is also made up of three subsystem blocks: the T1DM patient model, virtual stabilization, and controller. The response of the states of the system was generated using scope blocks.

The performance of the AIBC and IBC controllers were then evaluated using transient and steady state parameters: settling time, overshoot, and steady state error. The percentage improvement of the AIBC over the IBC based controller for blood glucose control was evaluated based on the equation:

$$\eta = \frac{K_{IBC} - K_{AIBC}}{K_{IBC}} \times 100\%$$

Where η represent percentage improvement of the developed AIBC over the integral backstepping controller (IBC), K_{IBC} is the value

obtained on integral backstepping controller and K_{AIBC} is the value obtained when AIBC was used.

RESULTS AND DISCUSSIONS

The results obtained based on the methodologies presented in chapter three that addressed the research objectives are discussed and presented in this section.

Simulation Results of AIBC with the T1DM Model

The results of the artificial pancreas system for Type 1 Diabetes Mellitus (T1DM) patients using the developed Adaptive Integral Backstepping Control (AIBC) under different Initial Conditions (IC) presented in the Table 9. The Figures below represent the system states.

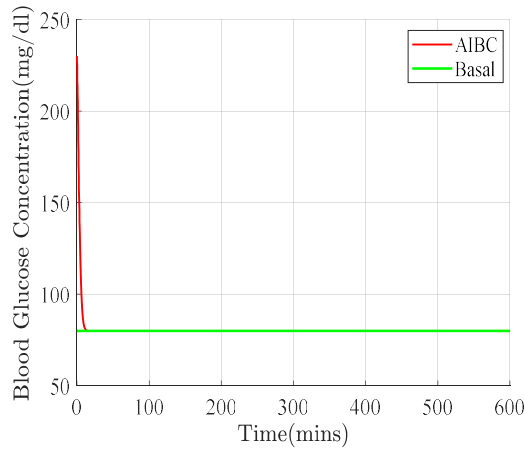


Figure 7: Regulation of Glucose Concentration during Hyperglycemia (230mg/dl)

Figure 7 shows the scenario of a hyperglycemic patient with Blood Glucose Concentration (BGC) at 230mg/dl (hyperglycemia state) exceeding the normal range (180mg/dl) and the desired trajectory to be tracked by the developed AIBC controller is the basal level

which is the optimal value of BGC in the blood stream whose constant value is 80mg/dl. From the Figure, it was observed that, the BGC was brought from the hyperglycemic state to the basal level by the developed AIBC controller without any instant of hypoglycemia.

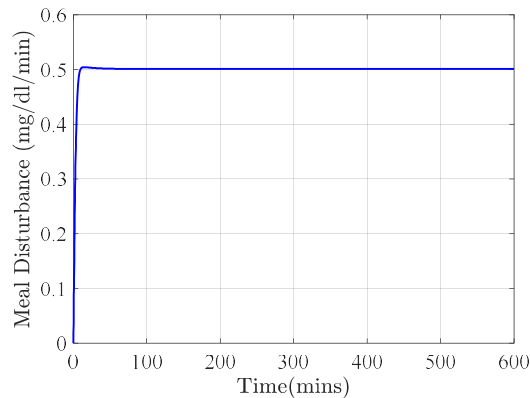


Figure 8: Meal Disturbance during Hyperglycemia (230mg/dl).

From Figure 8 shows meal disturbance. In type 1 diabetic patient the natural control of glucose is not working due to which external food taken by patient act as an external

disturbance. It was observed from the Figure that, disturbances lasted at $t = 8$ minutes.

Figure 8 shows the graphs of insulin infusion rate (control effort) obtained from simulation when BGC was at 230mg/dl.

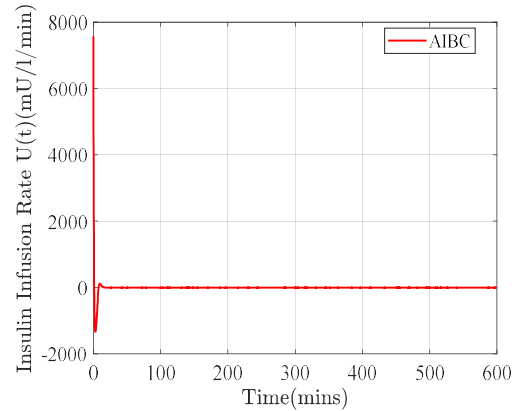


Figure 9: Insulin injection rate in presence of hyperglycemia

Figure 9 shows the response plot of stabilizing control action (insulin infusion rate) that stabilized the T1DM patient in the presence of hyperglycemia and meal disturbance. From the Figure, it was observed that, the developed AIBC controller exhibit large amount of the control action at early time when the system states exhibit changes that is fall and rise of amplitude. After some time, the system states stabilized to the zero equilibrium point and less amount of the control action was required.

Simulation Results of AIBC and IBC with the T1DM Model

The results obtained for the simulation of both Adaptive Integral Backstepping Control (AIBC) and Integral Backstepping Control (IBC) with Artificial Pancreas System (APS) for T1DM patient presented in Figure 10 and Figure 11 were obtained by considering the blood glucose level at 230mg/dl. The response of the system is shown in Figure 10:

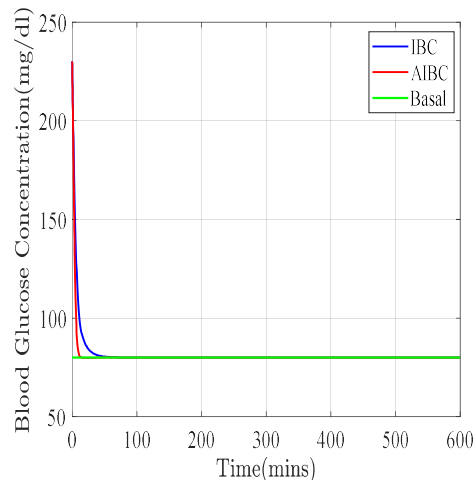


Figure 10: Blood Glucose Response at 230mg/dL

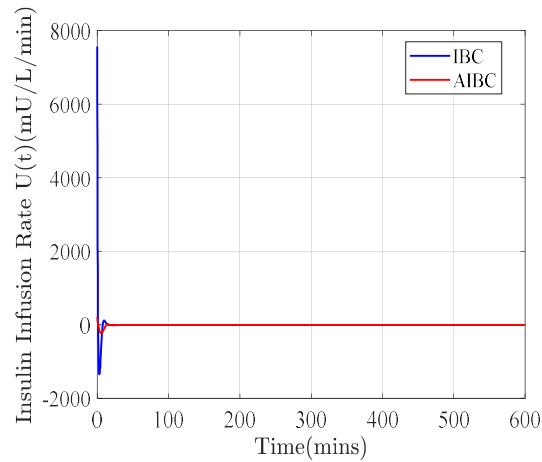


Figure 11: Insulin Infusion Rate

Figure 11 shows Insulin Infusion rate in the case of a hyperglycemic patient with blood while Figure 10 shows the glucose concentration at 230mg/dl (i.e., hyperglycemia state) exceeding the normal range of 70mg/dl to 180mg/dl. The AIBC based controller generated a manipulated signal so that the system tracked the basal level which is the optimal value of BGC in the blood stream whose constant value is 80mg/dL. It was also observed that, the BGC was brought from the hyperglycemic state to the basal level faster by the AIBC which is the safe range for the diabetic patient without any instance of severe hypoglycemia (<50mg/dl). Unlike the Integral

Backstepping control (IBC) technique, which took longer time to converge to the basal level

Figure 11: shows the control input $u(t)$ that is infusion of insulin or insulin injected through pump into body of diabetes patient in the presence of hyperglycemia. It was observed from the Figure above, that injecting insulin using the developed AIBC scheme, there was a fall in the amplitude and later settle at equilibrium point that is, and there is no need for further insulin infusion. This implies the patient is in the recovery stage. Unlike control input for IBC which shows rapid changes.

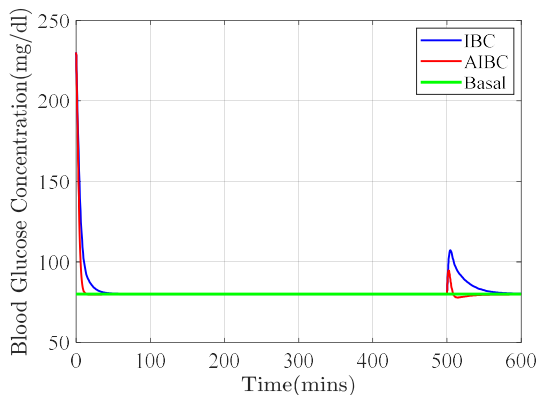


Figure 12: BGR in Hyperglycemia State and External Disturbance at 25mg/dl

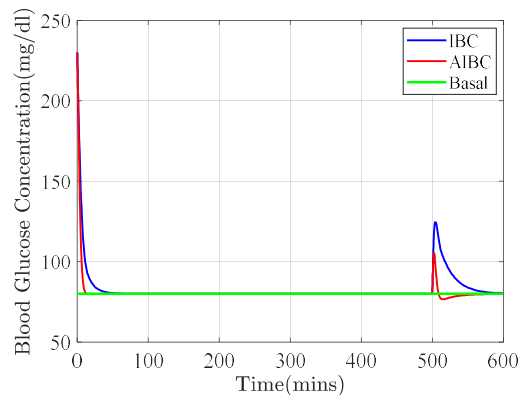


Figure 14: BGR in Hyperglycemia State and External Disturbance at 45mg/dl

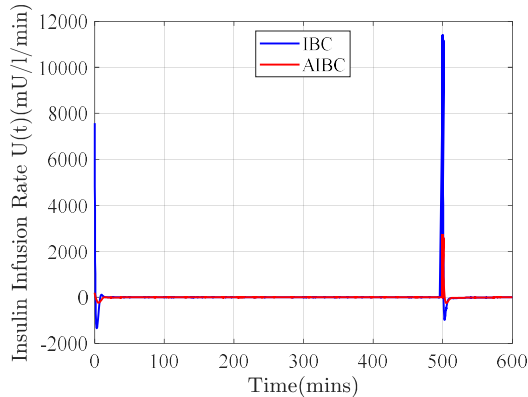


Figure 13: Insulin Infusion Rate in a Perturb Situation at 25mg/dl

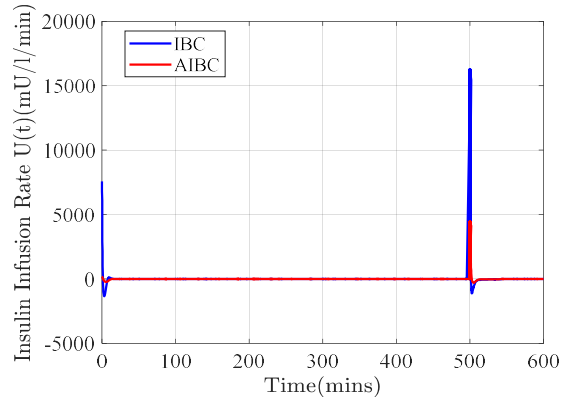


Figure 15: Insulin Infusion Rate in a Perturb Situation at 45mg/dl

Also, an external glucose dosage was introduced into the system to act as a disturbance at time $t = 500$ minutes in order to further validate the performance of the developed AIBC.

Case 1: Blood glucose at 230mg/dl when an impulse signal of 25mg/dl was introduced at time $t=500$ Minutes at duration of as shown in figure 12.

It was observed from the Figure 12 above that, after the appearance of the glucose dosage, error increase from 80mg/dl to 105mg/dl. In order to reduce the error to achieved the basal value, insulin was injected into the patient using the developed AIBC thereby reducing error to zero at time $t=540$ minutes, proving the superiority of the developed controller without any risk of hypoglycemia. In case of conventional IBC level of blood glucose was reduced to basal value at $t = 565$ minutes.

Figure 13 depicted the control effort that is the infusion insulin or insulin injected through pump into body of diabetes patient in the presence of hyperglycemia and external disturbance, administering insulin using the developed AIBC, there was a fall in the amplitude and later settle at equilibrium point that is, and there is no need for further administering of insulin. That is, the patient is at the verge of recovering while in the case of IBC, the control input shows rapid changes.

Case 2: Blood glucose at 230mg/dl when an impulse signal of 45mg/dl was introduced at time $t=500$ minutes

From figure 14, AIBC controller was able to track the reference signal (basal value) and it takes 78.2 minutes to totally stabilize the system, when the disturbance was introduced at time $t=500$ minutes. This shows clearly how AIBC controller guarantee better system performance in the presence of a disturbance. While the IBC based controller was able to trace the desired reference signal and bring the blood glucose concentration to basal value at time $t=90.4$ minutes after the introduction of disturbance at time $t=500$ minutes and at the duration of 8.2 minutes

Figure 15 represent the control effort in the presence of hyperglycemia and external disturbance. It can be seen from the Figure 17, that this also exhibit similar behavior to that of Figure 4.7 except the amplitudes of both controllers were high due to increase in magnitude of the signal.

Performance Comparison of the Developed AIBC based and IBC based Controllers

The performance of the controllers for T1DM patient blood glucose control was assessed on the basis of settling time, overshoot and steady state error as reported in Babar et al., (2019). The performance of the developed

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adaptive integral backstepping (AIBC) controller and IBC controller based on blood glucose

control of T1DM patients with respect to the performance metrics were presented in Table 5.

Table 4: Performance Comparison between the Developed AIBC and IBC Schemes

Performance Specification	Controller		Percentage Improvement (%)
	Developed AIBC	IBC	
Settling Time(minutes)	9.73	11.5	15.39
Overshoot (%)	No	No	
Steady state error	No	No	

Table 4 summarizes the performance comparison of the developed AIBC and that of IBC reported in the work of (Babar et al., 2019). It can be shown that both the controllers satisfy the design specification of settling time of less than 15mins. However, the developed AIBC has the overall improvement of 35.13% when compared to the design specification while it has 15.39% improvement in settling time when compared to the work reported by (Babar et al., 2019).

CONCLUSION AND RECOMMENDATION

The research presents development of an Adaptive Integral Backstepping controller (AIBC) of an artificial pancreas for Type 1 Diabetes Mellitus (T1DM) patient in order to address the issues of hyperglycemia during glycemic blood glucose regulation. The model of the adaptive parameters of the T1DM patient was developed in MATLAB/Simulink. Subsequently, the patient's model and the Integral Backstepping Control (IBC) technique was developed in MATLAB/Simulink. The Simulation of the developed system was carried out in MATLAB/Simulink 2019b using blood glucose level at 230mg/dl and the cases of an impulse signal to acts as an external glucose was introduced into the system at time t= 500 minutes. The performance evaluation of the results was carried out and compared to the system reported in the work of Babar et al., (2019) in terms of settling time, overshoot and steady state error. The simulation results reveal that the developed AIBC has the overall improvement of 35.13% when compared to the design specification while it has 15.39% improvement of settling time of Blood Glucose (BG) to the basal value for 230mg/dl. For

overshoot and steady state error both the work reported in Babar et al., (2019) and the developed AIBC recorded 0% for overshoot and steady state error.

REFERENCE

Abu-Rmieleh, A., Garcia-Gabin, W., and Zambrano, D. (2010). Internal model sliding mode control approach for glucose regulation in type 1 diabetes. *Biomedical Signal Processing and Control*, 5(2), 94-102.

Afrand, P., Yazdani, N., Moetamedzadeh, H., Naderi, F., and Panahi, M. (2012). Design and implementation of an expert clinical system for diabetes diagnosis. *Global Journal of Science, Engineering and Technology*, 3, 23-31.

Ahmad, Munir, F., and Munir, M. F. (2019). An adaptive backstepping based non-linear controller for artificial pancreas in type 1 diabetes patients. *Biomedical Signal Processing and Control*, 47, 49-56. doi:10.1016/j.bspc.2018.07.016

Ahmad, S., Ahmed, N., Ilyas, M., and Khan, W. (2017). Super twisting sliding mode control algorithm for developing artificial pancreas in type 1 diabetes patients. *Biomedical Signal Processing and Control*, 38, 200-211.

Alagoz, B. B., Deniz, F. N., Keles, C., and Tan, N. (2015). Disturbance rejection performance analyses of closed loop control systems by reference to disturbance ratio. *ISA transactions*, 55, 63-71.

Alam, W., Ali, N., Ahmad, S., and Iqbal, J. (2018). Super twisting control algorithm

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- for blood glucose regulation in type 1 diabetes patients. Paper presented at the 2018 15th International Bhurban Conference on Applied Sciences and Technology (IBCAST).
- Alphinas, R. A., Hansen, H. H., and Tambo, T. (2017). Comparison of conventional closed-loop controller with an adaptive controller for a disturbed thermodynamic system. Paper presented at the 2017 Evolving and Adaptive Intelligent Systems (EAIS).
- Amiri, N., Ramirez-Serrano, A., and Davies, R. J. (2013). Integral backstepping control of an unconventional dual-fan unmanned aerial vehicle. *Journal of Intelligent & Robotic Systems*, 69(1-4), 147-159.
- Babar, S. A., Rana, I. A., Arslan, M., and Zafar, M. W. (2019). Integral Backstepping Based Automated Control of Blood Glucose in Diabetes Mellitus Type 1 Patients. *IEEE Access*, 7, 173286-173293.
- Boiroux, D., Batora, V., Hagdrup, M., Wendt, S. L., Poulsen, N. K., Madsen, H., and Jørgensen, J. B. (2018). Adaptive model predictive control for a dual-hormone artificial pancreas. *Journal of Process Control*, 68, 105-117.
- Butt, R. S., Ahmad, I., Iftikhar, R., and Arsalan, M. (2019). Integral Backstepping and Synergetic Control for Tracking of Infected Cells During Early Antiretroviral Therapy. *IEEE Access*, 7, 69447-69455.
- Carrasco, D. S., Fu, Y., Goodwin, G. C., King, B. R., and Mediolì, A. M. (2014). Performance limitations arising in closed loop control of blood glucose in type 1 diabetes. *IFAC Proceedings Volumes*, 47(3), 2082-2087.
- Cobelli, C., Renard, E., and Kovatchev, B. (2011). Artificial pancreas: past, present, future. *Diabetes*, 60(11), 2672-2682.
- Colmegna, P., Garelli, F., De Battista, H., and Sánchez-Peña, R. (2018). Automatic regulatory control in type 1 diabetes without carbohydrate counting. *Control engineering practice*, 74, 22-32.
- Cooke, D. W., and Plotnick, L. (2008). Type 1 diabetes mellitus in pediatrics. *pediatr Rev*, 29(11), 374-384.
- Commerais, H., and Richard, P.-Y. (2012). Artificial pancreas for type 1 diabetes: closed-loop algorithm based on error dynamics shaping. *Journal of Process Control*, 22(7), 1219-1227
- Ehsani, M. (2007). Adaptive control of servo motor by MRAC method. Paper presented at the 2007 IEEE Vehicle Power and Propulsion Conference.
- Goharimanesh, M., Lashkaripour, A., Shariatnia, S., and Akbari, A. (2014). Diabetic control using genetic fuzzy-PI controller. *International Journal of Fuzzy Systems*, 16(2), 133-139.
- Haidar, A., Smaoui, M. R., Legault, L., and Rabasa-Lhoret, R. (2016). The role of glucagon in the artificial pancreas. *The lancet Diabetes & endocrinology*, 4(6), 476-479.
- Hu, R., and Li, C. (2015). A fuzzy-PID glucose control strategy for insulin therapy in type 1 diabetics. Paper presented at the 2015 IEEE International Conference on Mechatronics and Automation (ICMA).
- Khaqan A., Nauman.A.,Shuja. A, Khurshaid. A and Kim, K. (2022). An intelligent model-based effective approach for glycemic control in type I diabetes. *World Academy of Science, Engineering and Technology, International Journal of Medical, Health, Biomedical, Bioengineering and Pharmaceutical Engineering*, 8(11), 779-783.
- Kumareswaran, K., Evans, M. L., and Hovorka, R. (2009). Artificial pancreas: an emerging approach to treat Type 1 diabetes. *Expert review of medical devices*, 6(4), 401-410.
- León-Vargas, F., Garelli, F., De Battista, H., and Vehí, J. (2015). Postprandial response improvement via safety layer in closed-

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- loop blood glucose controllers. *Biomedical Signal Processing and Control*, 16, 80-87.
- Lunze, K., Singh, T., Walter, M., Brendel, M. D., and Leonhardt, S. (2013). Blood glucose control algorithms for type 1 diabetic patients: A methodological review. *Biomedical Signal Processing and Control*, 8(2), 107-119.
- Mahmud, F., Isse, N. H., Daud, N. A. M., and Morsin, M. (2017). Evaluation of PD/PID controller for insulin control on blood glucose regulation in a Type-I diabetes. Paper presented at the AIP Conference Proceedings.
- Malik, S., Perdeshi, S and Jaya, N. (2019). Design of adaptive controller based on Lyapunov stability for a CSTR. *World Academy of Science, Engineering and Technology International Journal of Electronics and Communication Engineering*, 8(1), 176-179.
- Marchetti, G., Barolo, M., Jovanovic, L., Zisser, H., and Seborg, D. E. (2008). An improved PID switching control strategy for type 1 diabetes. *IEEE Transactions on Biomedical Engineering*, 55(3), 857-865.
- Melling, C., Grisé, K., Hasilo, C., Fier, B., Milne, K., Karmazyn, M., and Noble, E. (2013). A model of poorly controlled type 1 diabetes mellitus and its treatment with aerobic exercise training. *Diabetes & metabolism*, 39(3), 226-235.
- Munir, F., Ahmad, I., and Naz, N. (2016). Backstepping based automatic blood glucose nonlinear controller for diabetes mellitus type 1 patients. *Advanced Science Letters*, 22(10), 2652-2656.
doi:<https://doi.org/10.1166/asl.2016.7011>
- Nath, A., Deb, D., Dey, R., and Das, S. (2018). Blood glucose regulation in type 1 diabetic patients: an adaptive parametric compensation control-based approach. *IET systems biology*, 12(5), 219-225.
- Nath, A., Dey, R., and Aguilar-Avelar, C. (2019). Observer based nonlinear control design for glucose regulation in type 1 diabetic patients: An LMI approach. *Biomedical Signal Processing and Control*, 47, 7-15.
- Ogata, K. (2010). *Modern control engineering*: Prentice hall.
- Organization, W. H. (2000). *General guidelines for methodologies on research and evaluation of traditional medicine*. Retrieved from
- Paiva, H. M., Keller, W. S., and da Cunha, L. G. R. (2020). Blood-Glucose Regulation Using Fractional-Order PID Control. *Journal of Control, Automation and Electrical Systems*, 31(1), 1-9.
- Pankaj, S., Kumar, J. S., and Nema, R. (2011). Comparative analysis of MIT rule and Lyapunov rule in model reference adaptive control scheme. *Innovative Systems Design and Engineering*, 2(4), 154-162.
- Parsa, N. T., Vali, A., and Ghasemi, R. (2014). Back stepping sliding mode control of blood glucose for type 1 diabetes. *World Academy of Science, Engineering and Technology, International Journal of Medical, Health, Biomedical, Bioengineering and Pharmaceutical Engineering*, 8(11), 779-783.
- Patel, D., Kumar, R., Laloo, D., and Hemalatha, S. (2012). Natural medicines from plant source used for therapy of diabetes mellitus: An overview of its pharmacological aspects. *Asian Pacific Journal of Tropical Disease*, 2(3), 239-250.
- Pietropaolo, M., and Le Roith, D. (2001). Pathogenesis of diabetes: our current understanding. *Clinical cornerstone*, 4(2), 1-16.
- Ronald Eric, Akif Rahmatillah and Riries Rulaningtyas (2023). Control system modeling of artificial pancreas based

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- on PID controller mechanism with Particle Swarm Optimization (PSO) tuning method: A methodological review. *Biomedical Signal Processing and Control*, 8(2), 107-119.
- Saleem, M. U., Farman, M., Ahmad, M., and Rizwan, M. (2017). Control of an artificial human pancreas. *Chinese journal of physics*, 55(6), 2273-2282.
- Sapiee, M., Selamat, H., Noordin, A., and Jahari, A. (2008). PI Controller design using model reference adaptive control approaches for a chemical process. Paper presented at the Proceedings of 2008 Student Conference on Research and Development (SCoReD 2008).
- Shekhar, A., and Sharma, A. (2018). Review of model reference adaptive control. Paper presented at the 2018 International Conference on Information, Communication, Engineering and Technology (ICICET).
- Singh, D., Patil, Y., Chougale, K., and Perdeshi, S. (2018). Optimal based PID control scheme for artificial pancreas system. *International Journal of Innovative Studies in Sciences and Engineering Technology (IJISSET)*, 3(4), 23-27.
- Stage, E., Ronneby, H., and Damm, P. (2003). Lifestyle change after gestational diabete. *Diabetes research and clinical practice*, 63(1), 67-72.
- doi:<https://doi.org/10.1016/j.diabres.2003.08.009>
- Swarnkar, P., Jain, S., and Nema, R. (2010). Effect of adaptation gain on system performance for model reference adaptive control scheme using MIT rule. *World Academy of science, engineering and technology*, 70, 621-626.
- Sylvester, D. D., and Munje, R. K. (2017). Back stepping SMC for blood glucose control of type-1 diabetes mellitus patients. A methodological review. *Biomedical Signal Processing and Control*, 8(2), 107-120.
- Thupili, V. R., and Srinivasan, K. (2009). Multi model based controller design for type 1 diabetic patients. Paper presented at the 2009 International Conference on Advances in Recent Technologies in Communication and Computing.
- Umopathy, C. (2011). *The State and Future of Closed Loop Insulin Pumps/Artificial Pancreas*. Case Western Reserve University.
- Vandana Dubey, Harsh Goud and Prakash Chandra Sharma (2021). Comparative analysis of PID tuning techniques for blood glucose level in type 1 diabetes patients. *Turkish Journal of Computer and Mathematics Education, Volumes 11(2021)*, 2948-2953

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