Documents

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Treatment for T1DM patients by a neuro-fuzzy inverse optimal controller including multi-step prediction

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Abstract

Diabetes Mellitus is a serious metabolic condition for global health associations. Recently, the number of adults, adolescents and children who have developed Type 1 Diabetes Mellitus (T1DM) has increased as well as the mortality statistics related to this disease. For this reason, the scientific community has directed research in developing technologies to reduce T1DM complications. This contribution is related to a feedback control strategy for blood glucose management in population samples of ten virtual adult subjects, adolescents and children. This scheme focuses on the development of an inverse optimal control (IOC) proposal which is integrated by neural identification, a multi-step prediction (MSP) strategy, and Takagi–Sugeno (T–S) fuzzy inference to shape the convenient insulin infusion in the treatment of T1DM patients. The MSP makes it possible to estimate the glucose dynamics 15 min in advance; therefore, this estimation allows the Neuro-Fuzzy-IOC (NF-IOC) controller to react in advance to prevent hypoglycemic and hyperglycemic events. The T–S fuzzy membership functions are defined in such a way that the respective inferences change basal infusion rates for each patient's condition. The results achieved for scenarios simulated in Uva/Padova virtual software illustrate that this proposal is suitable to maintain blood glucose levels within normoglycemic values (70–115 mg/dL); furthermore, this level remains less than 250 mg/dL during the postprandial event. A comparison between a simple neural IOC (NIOC) and the proposed NF-IOC is carried out using the analysis for control variability named CVGA chart included in the Uva/Padova software. This analysis highlights the improvement of the NF-IOC treatment, proposed in this article, on the NIOC approach because each subject is located inside safe zones for the entire duration of the simulation. © 2021 ISA

Index Keywords

Blood, Controllers, Fuzzy neural networks, Glucose, Membership functions, Patient treatment; Blood glucose management, Feedback control strategies, Fuzzy membership function, Inverse-optimal control, Multi-step prediction, Neural identification, Scientific community, Type 1 diabetes mellitus; Fuzzy inference; antidiabetic agent, insulin; adolescent, adult, algorithm, child, computer simulation, glucose blood level, human, insulin dependent diabetes mellitus; Adolescent, Adult, Algorithms, Blood Glucose, Child, Computer Simulation, Diabetes Mellitus, Type 1, Humans, Hypoglycemic Agents, Insulin

References

- Control, T.D., Group, C.T.R.
  The effect of intensive treatment of diabetes on the development and progression of long-term complications in insulin-dependent diabetes mellitus. The Diabetes Control and Complications Trial Research Group
  (1993) *N Engl J Med*, 329 (14), pp. 977-986.

- Turner, R.
  Intensive blood-glucose control with sulphonylureas or insulin compared with conventional treatment and risk of complications in patients with type 2 diabetes (UKPDS 33)
  (1998) *Lancet*, 352 (9131), pp. 837-853.

- DeFronzo, R., Ferrannini, E., Alberti, K., Zimmet, P.
  The classification and diagnosis of diabetes mellitus
  (2015) *International textbook of diabetes mellitus*, pp. 24-30.
  Sons J.W.&. 4th ed. John Wiley & Sons New Jersey, Middle Atlantic, U.S. [Ch. 1]

- DeFronzo, R.A.
  Epidemiology and risk factors for type 1 diabetes mellitus
  (2015) *International textbook of diabetes mellitus*, pp. 17-28.
  Sons J.W.&. 4th ed. John Wiley & Sons Oxford, U.K. [Ch. 2]

- Majithia, A.R., Wiltschko, A.B., Zheng, H., Walford, G.A., Nathan, D.M.
  Rate of change of premeal glucose measured by continuous glucose monitoring predicts postmeal glycemic excursions in patients with type 1 diabetes: Implications for therapy
  (2018) *J Diabetes Sci Technol*, 12 (1), pp. 76-82.

- Hovorka, R.
  Continuous glucose monitoring and closed-loop systems
  (2006) *Diabetic medicine*, p. 12.
  Wiley Online Library Cambridge, Massachusetts, U.S.

- Kux, L.
  Guidance for industry and food and drug administration staff; the content of investigational device exemption and premarket approval applications for artificial pancreas device systems; availability
  (2012) *Fed Regist*, 77 (226), pp. 1-63.

- Messori, M., Paolo Incremona, G., Cobelli, C., Magni, L.
  Individualized model predictive control for the artificial pancreas: In silico evaluation of closed-loop glucose control
  (2018) *IEEE Control Syst*, 38 (1), pp. 86-104.

- Magni, L., Forgione, M., Toffanin, C., Dalla Man, C., Kovatchev, B., De Nicolao, G.
  Run-to-run tuning of model predictive control for type 1 diabetes subjects: In silico trial
  (2009) *J Diabetes Sci Technol*, 3 (5), pp. 1091-1098.

- Messori, M., Ellis, M., Cobelli, C., Christofides, P.D., Magni, L.
  Improved postprandial glucose control with a customized Model Predictive Controller. In: Proceedings of the american control conference. p. 5108–15.

- Gondhalekar, R., Dassau, E., Doyle, F.J.
  Velocity-weighting to prevent controller-induced hypoglycemia in MPC of an artificial pancreas to treat T1DM. In: Proceedings of the american control conference. p. 1635–40.
- Ortmann, L., Shi, D., Dassau, E., Doyle, F.J., Leonhardt, S., Misgeld, B.J.
  Gaussian process-based model predictive control of blood glucose for patients with type 1 diabetes mellitus. In: 2017 asian control conference. p. 1092–7.
- Resalat, N., Youssef, J.E., Reddy, R., Jacobs, P.G.
  Design of a dual-hormone model predictive control for artificial pancreas with exercise model. In: Proceedings of the annual international conference of the IEEE engineering in medicine and biology society. p. 2270–3.
- Tang, F., Wang, Y.
  Design of Bi-hormonal artificial pancreas system using switching economic model predictive control. In: Chinese control conference. p. 4579–84.
- Wang, Q., Xie, J., Molenaar, P., Ulbrecht, J.
  Model predictive control for type 1 diabetes based on personalized linear time-varying subject model consisting of both insulin and meal inputs: In Silico evaluation. In: Proceedings of the american control conference. p. 5782–7.
- Colmegna, P., Sanchez-Pena, R.S., Gondhalekar, R.
  Control-oriented Linear Parameter-Varying model for glucose control in Type 1 Diabetes. In: IEEE conference on control applications. p. 410–5.
- Patek, S.D., Magni, L., Dassau, E., Hughes-Karvetski, C., Toffanin, C., De Nicolao, G.
  Modular closed-loop control of diabetes
  (2012) *IEEE Trans Biomed Eng*, 59 (11), pp. 2986-2999.
- Galadanci, J., Shafik, R.A., Mathew, J., Acharyya, A., Pradhan, D.K.
  A closed-loop control strategy for glucose control in artificial pancreas systems. In: Proceedings - 2012 international symposium on electronic system design. p. 295–9.
- Kovacs, L., Szalay, P., Benyo, B., Chase, G.J.
  , pp. 59-64.
  Asymptotic output tracking in blood glucose control. A case study. In: Proceedings of the IEEE conference on decision and control.
- Leon, B.S., Alanis, A.Y., Sanchez, E.N., Ornelas-Tellez, F., Ruiz-Velazquez, E.
  Neural inverse optimal control applied to type 1 diabetes mellitus patients
  (2013) *Analog Integr Circuits Signal Process*, 76 (3), pp. 343-352.
- Rios, Y.Y., García-Rodríguez, J.A., Sánchez, O.D., Sanchez, E.N., Alanis, A.Y., Ruiz-Velázquez, E., Arana-Daniel, N.
  , pp. 1-8.

Inverse optimal control using a neural multi-step predictor for T1DM treatment. In: Proceedings of the international joint conference on neural networks.

- Karahoca, A., Karahoca, D., Kara, A.
, pp. 1-4.
Diagnosis of diabetes by using adaptive neuro fuzzy inference systems. In: 2009 fifth international conference on soft computing, computing with words and perceptions in system analysis, decision and control.

- Geman, O., Chiuchisan, I., Toderean, R.
Application of Adaptive Neuro-Fuzzy Inference System for diabetes classification and prediction. In: 2017 E-health and bioengineering conference. p. 639–42.

- Lekkas, S., Mikhailov, L.
Evolving fuzzy medical diagnosis of Pima Indians diabetes and of dermatological diseases
(2010) *Artif Intell Med*, 50 (2), pp. 117-126.

- Nath, A., Dey, R., Balas, V.E.
Closed loop blood glucose regulation of type 1 diabetic patient using takagi-sugeno fuzzy logic control
(2018) *Advances in intelligent systems and computing*, pp. 286-296.
Springer Cham, Switzerland

- Alanis, A.Y., Sanchez, E.N., Loukianov, A.G.
Discrete-time adaptive backstepping nonlinear control via high-order neural networks
(2007) *IEEE Trans Neural Netw*, 18 (4), pp. 1185-1195.

- Quintero-Manriquez, E., Sanchez, E.N., Harley, R.G., Li, S., Felix, R.A.
Neural sliding mode control for induction motors using rapid control prototyping
(2017) *IFAC-PapersOnLine*, 50 (1), pp. 9625-9630.

- Rovithakis, G.A., Christodoulou, M.A.
Adaptive control with recurrent high-order neural networks: Theory and industrial applications
(2000), p. 196.
Springer London, U.K.

- Sanchez, E.N., Alanis, A.Y., Loukianov, A.G.
Discrete-time high order neural control: trained with Kalman filtering, vol. 112
(2008), p. 116.
Springer Science & Business Media Berlin, Germany

- Sanchez, E.N., Ornelas-Tellez, F.
Discrete-time inverse optimal control for nonlinear systems

(2013), p. 268.
CRC Press Boca Raton, Florida, U.S.

- Li, W., Todorov, E., Liu, D.
Inverse optimality design for biological movement systems
(2011) *IFAC Proc Vol*, 44 (1), pp. 9662-9667.

- Freeman, R.A., Kokotović, P.
Robust nonlinear control design
(2009), p. 255.
Birkhäuser Boston, Massachusetts, U.S.

- Ornelas, F., Sanchez, E.N., Loukianov, A.G.
Discrete-time nonlinear systems inverse optimal control: A control Lyapunov function approach. In: Proceedings of the IEEE international conference on control applications. p. 1431–6.

- Ornelas-Tellez, F., Sanchez, E.N., Loukianov, A.G., Navarro-Lopez, E.M.
Speed-gradient inverse optimal control for discrete-time nonlinear systems. In: Proceedings of the IEEE conference on decision and control. p. 290–5.

- Kirk, D.E.
Optimal control theory: an introduction
(1970), p. 564.
springer-v ed. Prentice-Hall Englewood Cliffs, New Jersey, U.S.

- Basar, T., Olsder, G.J.
Dynamic noncooperative game theory
(1999), p. 526.
2nd ed. Society for Industrial and Applied Mathematics Philadelphia, Pennsylvania, U.S.

- Ohsawa, T., Bloch, A.M., Leok, M.
Discrete Hamilton–Jacobi theory and discrete optimal control. In: Proceedings of the IEEE conference on decision and control. p. 5438–43.

- Al-Tamimi, A., Lewis, F., Abu-Khalaf, M.
Discrete-time nonlinear HJB solution using approximate dynamic programming: Convergence proof
(2008) *IEEE Trans Syst Man Cybern B*, 38 (4), pp. 943-949.

- Kovatchev, B.P., Breton, M., Dalla Man, C., Cobelli, C.
In silico preclinical trials: A proof of concept in closed-loop control of type 1 diabetes
(2009) *J Diabetes Sci Technol*, 3 (1), pp. 44-55.

- Man, C.D., Micheletto, F., Lv, D., Breton, M., Kovatchev, B., Cobelli, C.
The UVA/PADOVA type 1 diabetes simulator
(2014) *J Diabetes Sci Technol*, 8 (1), pp. 26-34.

- Chang, F.J., Chiang, Y.M., Chang, L.C.
Multi-step-ahead neural networks for flood forecasting
(2010) *Hydrol Sci J*, 52 (1), pp. 114-130.

- Takagi, T., Sugeno, M.
Fuzzy identification of systems and its applications to modeling and control
(1985) *IEEE Trans Syst Man Cybern*, SMC-15 (1), pp. 116-132.

- Lopes Souto, D., Lopes Rosado, E.
Use of carb counting in the dietary treatment of diabetes mellitus
(2010) *Nutr Hosp*, 25 (1), pp. 18-25.

- Institute of Medicine, D.
Summary tables, dietary reference intakes
(2005) *Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids*, pp. 1319-1331.
Elsevier Washington, D.C., U.S. [Ch. Summary Ta]

- Previato, H.D.R.D.A.
Carbohydrate counting in diabetes
(2016) *Nutr Food Technol: Open Access*, 2 (2), pp. 1-4.

- American Diabetes Association, P.S.
Nutrition recommendations and interventions for diabetes - a position statement
(2008) *Diabetes Care*, 31 (1), pp. S61-S78.

- Association, A.D.
All about carbohydrate counting
(2009),
American Diabetes Association URL

- Cinar, A.
Artificial pancreas systems: An introduction to the special issue
(2018) *IEEE Control Syst Mag*, 38 (1), pp. 26-29.

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