



Energy saving for building heating via a simple and efficient model-free control design: First steps with computer simulations

Hassane Abouaïssa, Ola Alhaj Hasan, Cédric Join, Michel Fliess, Didier Defer

► To cite this version:

Hassane Abouaïssa, Ola Alhaj Hasan, Cédric Join, Michel Fliess, Didier Defer. Energy saving for building heating via a simple and efficient model-free control design: First steps with computer simulations. 21st International Conference on System Theory, Control and Computing, ICSTCC 2017, Oct 2017, Sinaia, Romania. hal-01568899v3

HAL Id: hal-01568899

<https://polytechnique.hal.science/hal-01568899v3>

Submitted on 4 Sep 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Energy saving for building heating via a simple and efficient model-free control design: First steps with computer simulations

Hassane Abouaïssa*, Ola Alhaj Hasan†, Cédric Join‡¶, Michel Fliess§¶, and Didier Defer†

*LGI2A (EA 3926), Université d'Artois, 64200 Béthune, France. Email: hassane.abouaïssa@univ-artois.fr

†LGCgE (EA 4515), Université d'Artois, 64200 Béthune, France.

Email: eng.3ola@gmail.com, didier.defer@univ-artois.fr

‡CRAN (CNRS, UMR 7039), Université de Lorraine, BP 239, 54506 Vandœuvre-lès-Nancy, France.

Email: cedric.join@univ-lorraine.fr

§LIX (CNRS, UMR 7161), École polytechnique, 91128 Palaiseau, France. Email: Michel.Fliess@polytechnique.edu

¶A.L.I.E.N., 7 rue Maurice Barrès, 54330 Vézelize, France. Email: {michel.fliess, cedric.join}@alien-sas.com

¶Projet Non-A, INRIA Lille – Nord-Europe, France.

Abstract—The model-based control of building heating systems for energy saving encounters severe physical, mathematical and calibration difficulties in the numerous attempts that has been published until now. This topic is addressed here via a new *model-free* control setting, where the need of any mathematical description disappears. Several convincing computer simulations are presented. Comparisons with classic PI controllers and flatness-based predictive control are provided.

Keywords— Building heating, energy saving, model-free control, intelligent P controllers, PI controllers, flatness-based control, predictive control.

1. Introduction

The growing importance of energy saving explains the key rôle of heating, ventilation and air conditioning (HVAC). It raises many exciting questions (see, e.g., [31]). We concentrate here on the building heating system. This topic, according to [52], has not attracted enough investigation from the control community. Let us mention here Boolean control, predictive control, PIDs, optimal control, nonlinear control, partial differential equations, flatness-based control, fuzzy systems, neural nets, ... See, e.g., [3], [4], [6], [7], [8], [10], [11], [15], [16], [20], [25], [26], [27], [32], [36], [39], [44], [46], [49], [50], [52], [61], [64], [67], ... The more “advanced” control approaches, which are listed above, are model-based. Here again, like in most concrete situations, writing a “good” mathematical model, where constraints and perturbations might be severe, is quite beyond our reach especially if online calibration ought to be performed. Those facts explain why in industrial practice classic PIDs and Boolean control, which to a large extent preclude any mathematical modeling, are most popular in spite of some shortcomings: poor performances and delicate tuning.

The topic is addressed here via *model-free control* and their corresponding *intelligent* controllers [21]. This setting,

- where the need of any precise mathematical description disappears,

- which is

- inherently robust, since the perturbations are easily taken into account,
- easy to implement both from software and hardware viewpoints,

has already been successfully applied a number of times, and in many countries. See, e.g., the references in [21], [1] and the references therein, and [2], [5], [13], [14], [17], [18], [28], [29], [30], [35], [38], [40], [41], [42], [43], [45], [47], [48], [51], [53], [55], [56], [57], [62], [66], [68], [69], [70], [71], [73], [74], [75], [76], [78], ... Let us emphasize here [33] and [13].

Our communication is organized as follows. Section 2 describes a simple linear model for the purpose of computer simulations which are analyzed in Section 3. Comparisons may be found there with proportional-integral (PI) controllers and with flatness-based control. Some concluding remarks are presented in Section 4. The large literature, that is already available on model-free control, explains why we have not incorporated any summary on this topic and on the related intelligent controllers. Any interested reader in an easy-to-understand introduction is invited to look at [33] and [13].

2. Modeling for computer simulations

Several authors (see, e.g., [65]) emphasized the necessity to simplify a “full” mathematical description, which comprises partial differential equations like, of course, the Fourier heat equation. Many publications have been devoted to the derivation of a “simple” but “efficient” modeling (see, e.g., [6], [8], [63], [72], and the references therein). Like in [7], a linear model due to [19] is used:

$$\begin{cases} \dot{T}_{\text{int}} = \frac{Q}{C_a} - \frac{K_c}{C_a} (T_{\text{int}} - T_{\text{wall}}) - \frac{K_f}{C_a} (T_{\text{int}} - T_{\text{ext}}) \\ \dot{T}_{\text{wall}} = \frac{K_c}{C_w} (T_{\text{int}} - T_w) - \frac{K_{\text{ext}}}{C_a} (T_{\text{wall}} - T_{\text{ext}}) \end{cases} \quad (1)$$

T_{int} , which has to be controlled via the the heat input Q , (resp. T_{ext} , T_{wall}) is the inside (resp. outside, wall) temperature. The

other coefficients are suitable physical quantities. Their nominal values are borrowed from [12]: $C_a = 1400$, $C_w = 2200$, $K_c = 1.4$, $K_f = 0.004$, $K_{ext} = 0.04$.

T_{ext} should be viewed as a *perturbation* in the control-theoretic meaning of this word, *i.e.*, T_{ext} is not regulated.

3. Comparisons of computer simulations

3.1. Intelligent proportional controller

Start with the most important feedback device in model-free control, *i.e.*, the *intelligent proportional controller* (see [21], and [13], [33]), or *iP*:

$$u = -\frac{F_{estim} - \dot{y}^* - K_P e}{\alpha} \quad (2)$$

where y^* is the reference trajectory, $e = y - y^*$ is the tracking error, the usual tuning gain K_P and the parameter α are chosen by the practitioner, F_{estim} is an estimate of F in the *ultra-local model* $\dot{y} = F + \alpha u$. Set in Eq. (2) $\alpha = 0.5$, $K_P = -0.5$. It yields Figure 1 where the results are excellent with the exception of two large errors in the tracking: T_{ext} becomes too large and the control variable Q is non-negative. Figure 2 shows that those errors disappear if cooling is allowed, *i.e.*, if the sign of Q is arbitrary.

Remark 3.1. Lack of space prevents us from showing the excellent results obtained with values of the coefficients in Eq. (1) which are quite far from the nominal ones. Moreover, the tuning of our *iP* does not need to be modified. Parameter identification becomes thus irrelevant.

3.2. PI

Introduce the classic proportional-integral (PI) controller (see, *e.g.*, [9]):

$$Q = k_p e + k_i \int e \quad (3)$$

where $e = y - y^*$ is the tracking error, k_p , k_i are the usual tuning gains. Set $k_p = -0.5$, $k_i = -0.01$. If, like too often in the industrial world, we leave a step between two different setpoints, Figures 3 and 1 show a significant performance deterioration. When this step is replaced by the same smooth reference trajectory used in Section 3.1, Figures 4 and 1 become almost identical. This result is not surprising. It is known [21] that *iPs* and *PIs* are equivalent in some sense.

Remark 3.2. In order to avoid steps we could have also employed *setpoint ramping* (see, *e.g.*, [37]).

3.3. Flatness-based predictive control

3.3.1. Generalities. Flatness-based control, which was introduced more than 25 years ago [23], certainly is one of the very few academic advances which have become popular in the industrial world (see also, *e.g.*, [9], [24], [34], [54], [58], [59], [77]). It might be viewed as another way of doing predictive

control, but without any optimization technique. From this standpoint, the first Eq. in (1) yields

$$Q^* = C_a \left(\dot{T}_{int}^* + \left(\frac{K_c}{C_a} + \frac{K_f}{C_a} \right) T_{int}^* \right)$$

where T_{int}^* is the reference trajectory for the internal temperature and Q^* the corresponding open-loop control. The closed-loop control reads $Q = Q^* + C(e)$, where $C(e)$ is some regulator.

3.3.2. P. $C(e)$ is a static state-feedback, *i.e.*, nothing else than a trivial P controller. Determine it by imposing a pole equal to 0.01. The results in Figure 5 are poor. The perturbation represented by the external temperature cannot be rejected if it is not measured.

Remark 3.3. Let us add however that such a perturbation might be measured and therefore rejected via some appropriate tools (see, *e.g.*, [22]).¹

3.3.3. PI. $C(e)$ is now a PI (3). The results in Figure 6, where the gains are tuned such that there is a double pole equal to -0.005 , are rather good. Note however that the control input fluctuates too quickly. With a double pole equal to -0.001 , the comparison of performances displayed in Figure 7 and Figure 1 show a poor robustness with respect to noises.

Remark 3.4. Section 3.3 confirms that a model-based standpoint might be cumbersome and, therefore, inappropriate.

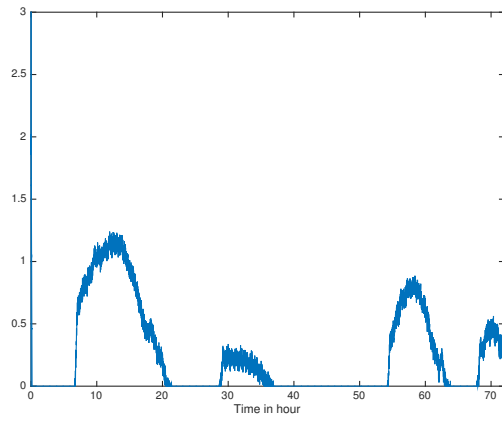
4. Conclusion

Satisfactory computer simulations were presented via model-free control and with a great ease. They will soon be tested in a real building and hopefully confirmed. The excellent results which were recently obtained with respect to an experimental greenhouse [33] should make us optimistic.

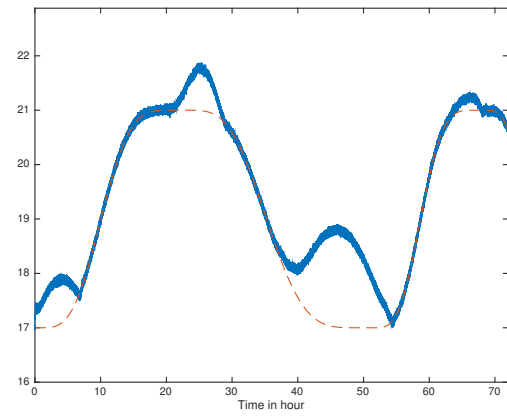
References

- [1] H. Abouaïssa, M. Fliess, C. Join, On ramp metering: Towards a better understanding of ALINEA via model-free control. *Int. J. Contr.*, 90, 1018-1026, 2017.
- [2] J.T. Agee, I.E. Davidson, L.T. Kombani, Intelligent proportional integral control of a polar axis solar tracker. *Power Syst. Conf.*, Clemson, 2016.
- [3] A. Afram, F. Janabi-Sharifi, Theory and applications of HVAC control systems – A review of model predictive control (MPC). *Building Environ.*, 72, 343-355, 2014.
- [4] A. Afram, F. Janabi-Sharifi, A.S. Funga, K. Raahemifar, Artificial neural network (ANN) based model predictive control (MPC) and optimization of HVAC systems: A state of the art review and case study of a residential HVAC system. *Energ. Buildings*, 141, 96-113, 2017.
- [5] Y. Al Younes, A. Drak, H. Noura, A. Rabhi, A. El Hajjaji, Robust model-free control applied to a quadrotor UAV. *J. Intellig. Robot. Syst.*, 84, 37-52, 2016.
- [6] O. Alhaj Hasan, *Optimization of Building Energy Consumption Using Simplified Models and New Control Methods*. Thèse, Université Lille 1, 2014.

1. Such a control design is often called *Active Disturbance Rejection Control*, or *ADRC* (see, *e.g.*, [60] and the references therein).

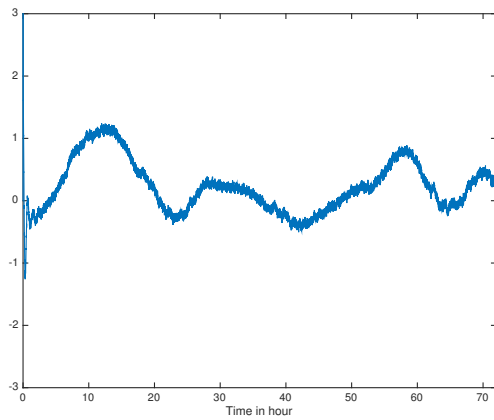


(a) Control

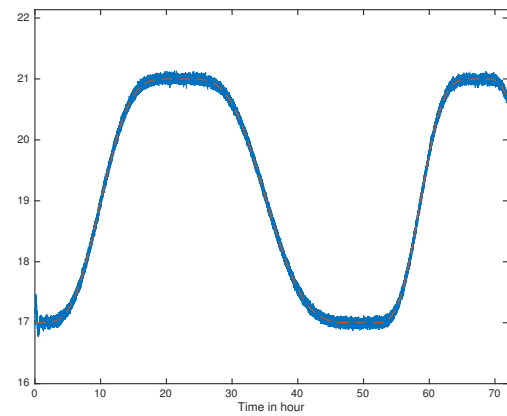


(b) Reference (- -) and temperature

Figure 1. iP with heating

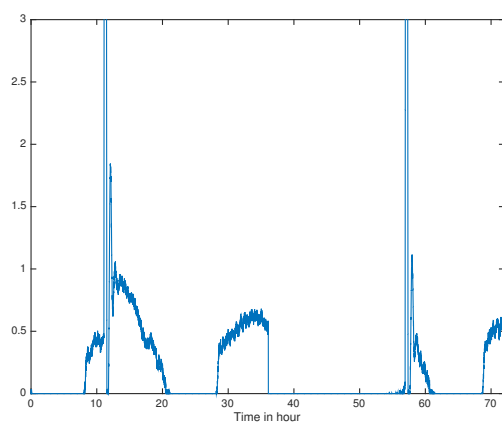


(a) Control

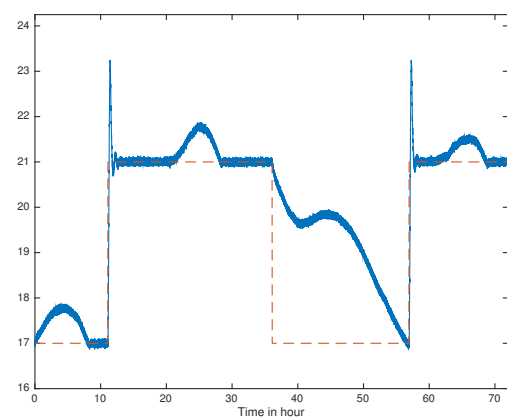


(b) Reference (- -) and temperature

Figure 2. iP with heating and cooling

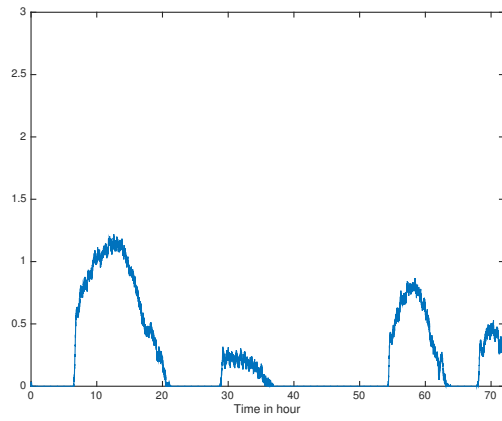


(a) Control

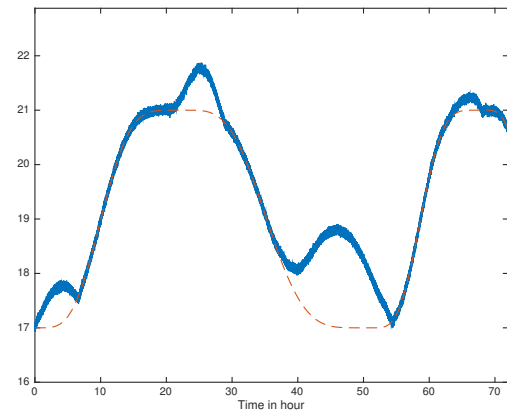


(b) Reference (- -) and temperature

Figure 3. PI with steps

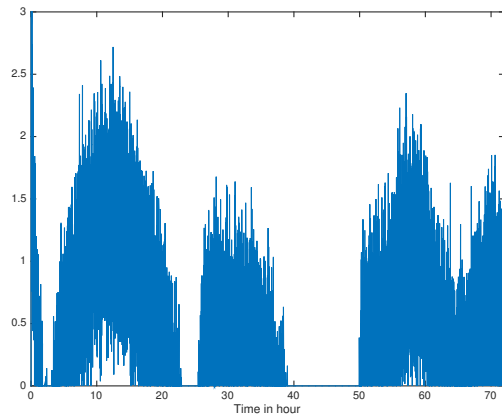


(a) Control

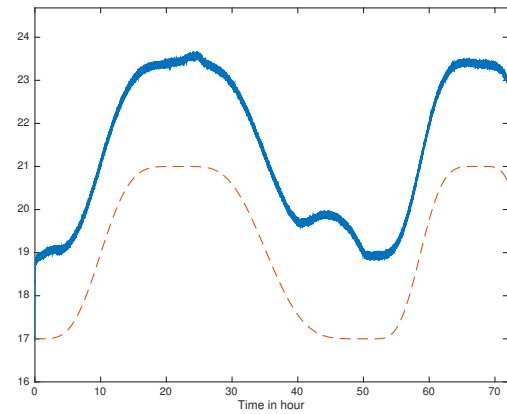


(b) Reference (- -) and temperature

Figure 4. PI with a smooth reference trajectory

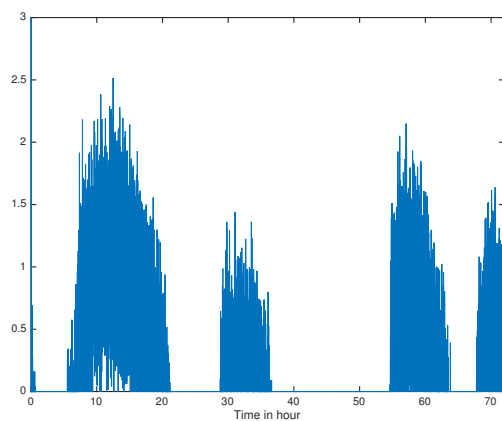


(a) Control

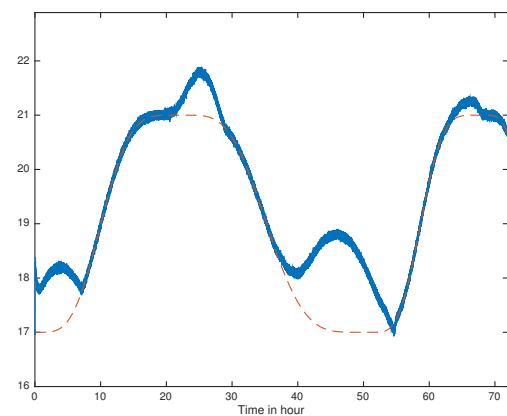


(b) Reference (- -) and temperature

Figure 5. Flatness and P

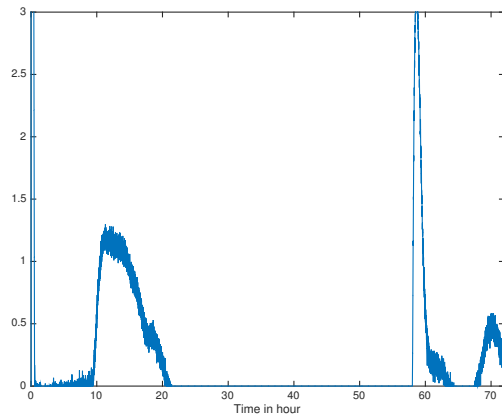


(a) Control

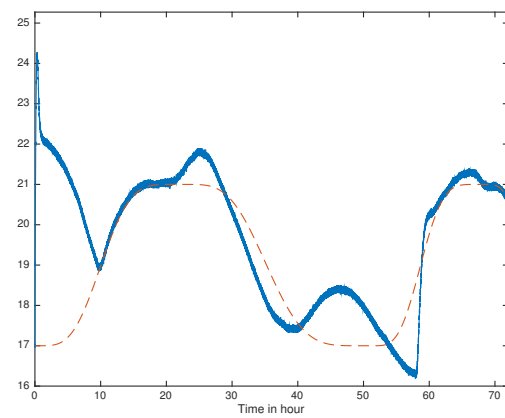


(b) Reference (- -) and temperature

Figure 6. Flatness and PI



(a) Control



(b) Reference (---) and temperature

Figure 7. Flatness and PI with “small” poles

- [7] O. Alhaj Hasan, H. Abouaissa, I. Shahrou, D. Defer, Building energy consumption flatness-based control using algebraic on-line estimation. *Ener. Efficient.*, 10, 657-671, 2017.
- [8] O. Alhaj Hasan, D. Defer, I. Shahrou, A simplified building thermal model for the optimization of energy consumption: Use of a random number generator, *Energ. Buildings*, 82, 322–329, 2014.
- [9] K.J. Åström, R.M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, 2008.
- [10] A. Aswani, N. Master, J. Taneja, D. Culler, C. Tomlin. Reducing transient and steady state electricity consumption in HVAC using learning-based model-predictive control. *Proc. IEEE*, 100, 240-253, 2012.
- [11] R. Bălan, J. Cooper, K.-M. Chao, S. Stana, R. Donca, Parameter identification and model based predictive control of temperature inside a house. *Energ. Buildings*, 43, 748–758, 2011.
- [12] R. Bălan, R. Donca, A. Balan, A. Pleșa, L. Pacurar, V. Muresan, Thermal modelling and temperature control of a house. *Roman. Rev. Precis. Mech. Opt. Mechatron.*, 39, 59-62, 2011.
- [13] O. Bara, M. Olama, S. Djouadi, T. Kuruganti, M. Fliess, C. Join, Model-free load control for high penetration of solar photovoltaic generation. *49th North Amer. Power Symp.*, Morgantown, 2017. Online: <https://hal.archives-ouvertes.fr/hal-01558647/en/>
- [14] A. Ben Hmedi, T. Bakir, S. B. inczak, A. Sakly, Model free control for muscular force by functional electrical stimulation using pulse width modulation. *4th Int. Conf. Contr. Engin. Informat. Techno.*, Hammamet, 2016.
- [15] T. Berthou, P. Stabat, R. Salvazet, D. Marchio, Optimal control for building heating: An elementary school case study. *13th Conf. Int. Building Perform. Simula. Assoc.*, Chambéry, 2013.
- [16] G. Bianchini, M. Casini, A. Vicino, D. Zarrilli, Demand-response in building heating systems: A model predictive control approach. *Appl. Energ.*, 168,159-170, 2016.
- [17] L. Cao, H. Li, H. Zhang, Model-free power control of front-end PFC AC/DC converter for on-board charger. *8th IEEE Int. Conf. Power Electron. Motion Contr.*, Hefei, 2016.
- [18] A.N. Chand, M. Kawanishi, T. Narikiyo, Non-linear model-free control of flapping wing flying robot using iPID. *IEEE Int. Conf. Robot. Automat.*, Stockholm, 2016.
- [19] J.A. Crabb, N. Murdoch, J.M. Penman, A simplified thermal response model. *Building Serv. Engin. Res. Techno.*, 8, 13-19, 1987.
- [20] P.M. Ferreira, A.E. Ruano, S. Silva, E.Z.E. Conceição, Neural networks based predictive control for thermal comfort and energy savings in public buildings. *Energ. Buildings*, 55, 238-251, 2012.
- [21] M. Fliess, C. Join, Model-free control. *Int. J. Contr.*, 86, 2228-2252, 2013.
- [22] M. Fliess, C. Join, H. Sira-Ramírez, Non-linear estimation is easy. *Int. J. Model. Identif. Contr.*, 4, 12-27, 2008.
- [23] M. Fliess, J. Lévine, P. Martin, P. Rouchon, Flatness and defect of non-linear systems: introductory theory and examples. *Int. J. Contr.* 61, 1327-1361, 1995.
- [24] M. Fliess, R. Marquez, Continuous-time linear predictive control and flatness: a module-theoretic setting with examples. *Int. J. Contr.*, 73, 606-623, 2000.
- [25] R.W. Hittle, D.C. Hittle, *Control Systems for Heating, Ventilating, and Air Conditioning* (6th ed.). Springer, 2003.
- [26] I. Hazyuk, C. Ghiaus, D. Penhouet, Optimal temperature control of intermittently heated buildings using Model Predictive Control: Part II – Control algorithm. *Building Environm.*, 51, 388–394, 2012.
- [27] S.D. Howell, P.V. Johnson, P.W. Duck, A rapid PDE-based optimization methodology for temperature control and other mixed stochastic and deterministic systems. *Energ. Buildings*, 43, 1523-1530, 2011.
- [28] J.-H. Jeong, D.-H. Lee, M. Kim, W.H. Park, G.-S. Byun, The study of the electromagnetic robot with a four-wheel drive and applied I-PID system. *J. Electric. Engin. Techno.*, 12, 1634-1640, 2017.
- [29] C. Join, J. Bernier, S. Mottelet, M. Fliess, S. Rechdaoui-Guérin, S. Azimi, V. Rocher, A simple and efficient feedback control strategy for wastewater denitrification. *20th World Congr. Int. Feder. Automat. Contr.*, Toulouse, 2017. <https://hal.archives-ouvertes.fr/hal-01488199/en/>
- [30] G.H. Kim, O.-H. Kwon, A.-S. Oh, The study of model-free control system based on intelligent PID controller. *Information*, 19, 2693-2698, 2016.
- [31] J. Khazaii, *Energy-Efficient HVAC Design*, Springer, 2014.
- [32] C. Koch-Ciobotaru, Model predictive control for inside temperature of an energy efficient building. V.E. Balas, J. Fodor, A.R. Várkonyi-Kóczy, J. Dombi, L.C. Jain (Eds): *Soft Computing Applications*, pp. 197-208, Springer, 2013.
- [33] F. Lafont, J.-F. Balmat, N. Pessel, M. Fliess, A model-free control strategy for an experimental greenhouse with an application to fault accommodation. *Comput. Electron. Agricult.*, 100, 139-149, 2015.
- [34] J. Lévine, *Analysis and Control of Nonlinear Systems: A Flatness-based Approach*, Springer, 2009.
- [35] S. Li, H. Wang, Y. Tian, A. Aitouch, J. Klein, Direct power control of DFIG wind turbine systems based on an intelligent proportional-integral sliding mode control. *ISA Trans.*, 64, 431-439, 2016.

- [36] X. Li, J. Wen, Review of building energy modeling for control and operation. *Renew. Sustain. Energ. Rev.*, 37, 517-537, 2014.
- [37] B.G. Lipták, *Process Control*. Butterworth-Heinemann, 1995.
- [38] S. Liu, Z. Hou, J. Zheng, Attitude adjustment of quadrotor aircraft platform via a data-driven model free adaptive control cascaded with intelligent PID. *Chinese Contr. Decis. Conf.*, Yinchuan, 2016.
- [39] X. Ma, J. Dong, S.M. Djouadi, J.J. Nutaro, T. Kuruganti, Stochastic control of energy efficient buildings: A semidefinite programming approach. *IEEE Int. Conf. Smart Grid Comm*, Miami, 2015.
- [40] S. Maalej, A. Kruszewski, L. Belkoura, Robust control for continuous LPV system with restricted-model-based control. *Circ. Syst. Sign. Process.*, 36, 2499-2520, 2017.
- [41] L. Menhour, B. d'Andréa-Novet, M. Fliess, D. Gruyer, H. Mounier, An efficient model-free setting for longitudinal and lateral vehicle control. Validation through the interconnected pro-SiVIC/RTMaps prototyping platform. *IEEE Trans. Intel. Transport. Syst.*, 2017. DOI: 10.1109/TITS.2017.2699283
- [42] L. Michel, O. Ghibaudo, O. Messal, A. Kedous-Lebouc, C. Boudinet, F. Blache, A. Labonne, Model-free based digital control for magnetic measurements. 2017. arXiv:1703.05395
- [43] L. Michel, O. Ghibaudo, M. Oualid, A. Lebouc, C. Boudinet, F. Blache, A. Labonne, Commande "sans modèle" pour l'asservissement numérique d'un banc de caractérisation magnétique. 2^e Symp. Gén. Électr., Grenoble, 2016.
- [44] N. Mendes, G.H.C. Oliveira, H.X. Araújo, L.S. Coelho, A Matlab-based simulation tool for building thermal performance analysis. *8th Int. IBPSA Conf.*, Eindhoven, 2003.
- [45] T. MohammadRidha, M. Aït-Ahmed, L. Chailloux, M. Krempf, I. Guilhem, J.-Y. Poirier, C.H. Moog, Model free iPID control for glycemia regulation of type-1 diabetes. *IEEE Trans. Biomed. Engin.*, 2017. DOI: 10.1109/TBME.2017.2698036
- [46] S.N. Murray, B.P. Walsh, D. Kelliher, D.T.J. O'Sullivan, Multi-variable optimization of thermal energy efficiency retrofitting of buildings using static modelling and genetic algorithms: A case study. *Building Environ.*, 75, 98-107, 2014.
- [47] J. Pardelhas, M. Silva, L. Mendonça, L. Baptista, Speed control of an experimental pneumatic engine. P. Garrido, F. Soares, A.P. Moreira (Eds): *Controlo 2016*, Lect. Notes Electr. Engin. 402, pp. 821-829. Springer, 2017.
- [48] P. Polack, B. d'Andréa-Novet, M. Fliess, A. de La Fortelle, L. Menhour, Finite-time stabilization of longitudinal control for autonomous vehicles using an adaptive model-free approach. *20th World Congr. Int. Feder. Automat. Contr.*, Toulouse, 2017.
<https://hal.archives-ouvertes.fr/hal-01498358/en/>
- [49] R. Ooka, K. Komamura, Optimal design method for building energy systems using genetic algorithms. *6th Int. Conf. Indoor Air Qualit. Ventil. Energy Conserv. Buildings*, Sendai, 2007.
- [50] B. Paris, J. Eynard, S. Grieu, T. Talbert, M. Polit, Heating control schemes for energy management in buildings. *Energ. Buildings*, 42, 1908-1917, 2010.
- [51] R.E. Precup, M.-B. Radac, R.-C. Roman, E.M. Petriuc, Model-free sliding mode control of nonlinear systems: Algorithms and experiments. *Informat. Sci.*, 381, 176-192, 2017..
- [52] S. Prívara, J. Šíroký, L. Ferkel, J. Cigler, Model predictive control of a building heating system: The first experience. *Energ. Buildings*, 43, 564-572, 2011.
- [53] M.B. Radac, R.-E. Precup, Model-free constrained data-driven iterative reference input tuning algorithm with experimental validation. *Int. J. Gen. Syst.*, 45, 455-476, 2016.
- [54] G.G. Rigatos, *Nonlinear Control and Filtering Using Differential Flatness Approaches – Applications to Electromechanical Systems*, Springer, 2015.
- [55] R.-C. Roman, R.-E. Precup, M.-B. Radac, Model-free fuzzy control of twin rotor aerodynamic systems. *25th Med. Conf. Contr. Automat., Valetta*, 2017.
- [56] R.-C. Roman, M.-B. Radac, R.-E. Precup, Multi-input-multi-output system experimental validation of model-free control and virtual reference feedback tuning techniques. *IET Contr. Theory Appl.*, 10, 1395-1403, 2016.
- [57] L. Sidhom, I. Chihi, S. Sahraoui, A. Abdelkrim, Intelligent-PI controller for electro-hydraulic system. *4th Int. Conf. Contr. Engin. Inform. Techno.*, Hammamet, 2016.
- [58] F. Rotella, I. Zambettakis, Commande des systèmes par platitude. *Techniques de l'Ingénieur S7450 V1*, 2007.
- [59] H. Sira-Ramírez, S. K. Agrawal, *Differentially Flat Systems*. Marcel Dekker, 2004.
- [60] H. Sira-Ramírez, A. Luviano-Juárez, M. Ramírez-Neria, E.W. Zurita-Bustamante, *Active Disturbance Rejection Control of Dynamic Systems: A Flatness Based Approach*. Butterworth-Heinemann, 2017.
- [61] J. Šíroký, F. Oldewurtel, J. Cigler, S. Prívara, Experimental analysis of model predictive control for an energy efficient building heating system. *Appl. Energ.*, 88, 3079-3087, 2011.
- [62] P. Ľapák, M. Huba, Laboratory model of thermal plant identification and control. *IFAC-PapersOnLine*, 49-6, 2016.
- [63] B. Tashtoush, M. Molhim, M. Al-Rousan, Dynamic model of an HVAC system for control analysis. *Energy*, 30, 1729-1745, 2005.
- [64] C. Turhan, S. Simani, I. Zajic, G.G. Akkurt, Analysis and application of advanced control strategies to a heating element nonlinear model. *IOP Conf. Series: J. Phys. Conf. Series*, 783, 2017.
doi:10.1088/1742-6596/783/1/012027
- [65] C.P. Underwood, An improved lumped parameter method for building thermal modelling. *Energ. Buildings*, 79, 191-201, 2014.
- [66] H. Wang, S. Li, Y. Tian, A. Aitouche, Intelligent proportional differential neural network control for unknown nonlinear system. *Stud. Informat. Contr.*, 25, 445-452, 2016.
- [67] S. Wang, Z. Ma, Supervisory and optimal control of building HVAC systems: A review. *HVAC&R*, 14, 3-32, 2008.
- [68] J. Wang, H. Mounier, S.-I. Niculescu, Event-driven model-free control in motion control with comparisons. *IMA J. Math. Contr. Informat.*, 32, 1-21, 2016.
- [69] H. Wang, Y. Tian, S. Han, X. Wang, ZMP theory-based gait planning and model-free trajectory tracking control of lower limb carrying exoskeleton system. *Stud. Informat. Contr.*, 26, 161-170, 2017.
- [70] H. Wang, X. Ye, Y. Tian, G. Zheng, N. Christov, Model-free based terminal SMC of quadrotor attitude and position. *IEEE Trans. Aerosp. Electron. Syst.*, 52, 2519-2528, 2016.
- [71] H.P. Wang, D. Zheng, Y. Tian, High pressure common rail injection system modeling and control. *ISA Trans.*, 63, 265-273, 2016.
- [72] S. Wu, J.-Q. Sun, A physics-based linear parametric model of room temperature in office buildings. *Building Environ.*, 50, 1-9, 2012.
- [73] Y. Xin, Z.-C. Qin, W.-G. Wu, J.-Q. Sun, Partial model-free control of a 2-input and 2-output helicopter system. *9th Europ. Nonlin. Dynam. Conf.*, Budapest, 2017.
- [74] C.-Y. Yu, J.-L. Wu, Intelligent PID control for two-wheeled inverted pendulums. *Int. Conf. System Sci. Engin.*, Puli, 2016.
- [75] X. Zhang, *Model-free motion control of positioning stage*. Delft University of Technology: Master Thesis, 2016.
- [76] X. Zhang, H. Wang, Y. Tian, L. Peyrodie, X. Wang, Model-free based neural network control with time-delay estimation for lower extremity exoskeleton. *Neurocomput.*, 2017
- [77] M. Zeitz, Differenzielle Flachheit: Eine nützliche Methodik auch für lineare SISO-Systeme. *Automatisierungstechn.*, 58, 5-13, 2010.
- [78] Y. Zhou, H. Li, H. Yao, Model-free control of surface mounted PMSM drive system. *IEEE Int. Conf. Indus. Techno.*, Taipei, 2016.