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***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.*, [28]). We concentrate here on the building heating system. This topic, according to [38], 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.*, [2], [3], [4], [5], [6], [8], [10], [13], [14], [17], [24], [25], [26], [29], [31], [33], [34], [35], [36], [37], [38], [43], [45], [47], ...). 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 [18]. 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 all over the world.[1] Some applications are patented. Let us cite here for obvious reasons only [30] and [12].

Our communication is organized as follows. Section 2 provides a brief presentation of model-free control and of the corresponding intelligent P controllers. Section 3 describes a simple linear model for the purpose of computer simulations which are analyzed in Section 4. Comparisons may be found there with proportional-integral controllers and with flatness-based control. Some concluding remarks are presented in Section 5.

2. Model-free control and intelligent controllers[2]

2.1. The ultra-local model

Replace the unknown global description by the *ultra-local model*:

$$\dot{y} = F + \alpha u \tag{1}$$

where

- the control and output variables are u and y,
- the derivation order of y is 1 like in most concrete situations,
- $\alpha \in \mathbb{R}$ is chosen by the practitioner such that αu and $\dot{y}$ are of the same magnitude.

The following explanations on F might be useful:

- F is estimated via the measure of u and y,
- F subsumes not only the unknown system structure but also any perturbation.

1. See, *e.g.*, the references in [18], and [1], [12] and the references therein.
2. See [18] for more details.

2.2. Intelligent controllers

The loop is closed by an *intelligent proportional controller*, or *iP*,

$$u = -\frac{F - \dot{y}^\star - K_P e}{\alpha} \tag{2}$$

where

- $y^\star$ is the reference trajectory,
- $e = y - y^\star$ is the tracking error,
- K_P is the usual tuning gain.

Combining Equations (1) and (2) yields:

$$\dot{e} = K_P e$$

where F does not appear anymore. The tuning of K_P, in order to insure local stability, becomes therefore quite straightforward. This is a major benefit when compared to the tuning of classic PIDs.

Remark 2.1. An appropriate choice of $y^\star$ is of utmost importance. Let us emphasize that this step is almost always knowledge-based.

2.3. Estimation of F

The calculations below stem from new estimation techniques (see [22], [23], and [41]).

2.3.1. First approach. The term F in Equation (1) may be assumed to be "well" approximated by a piecewise constant function F_{est}. Rewrite then Equation (1) in the operational domain (see, *e.g.*, [16]):

$$sY = \frac{\Phi}{s} + \alpha U + y(0)$$

where Φ is a constant. We get rid of the initial condition $y(0)$ by multiplying both sides on the left by $\frac{d}{ds}$:

$$Y + s\frac{dY}{ds} = -\frac{\Phi}{s^2} + \alpha\frac{dU}{ds}$$

Noise attenuation is achieved by multiplying both sides on the left by s^{-2}. It yields in the time domain the realtime estimate, thanks to the equivalence between $\frac{d}{ds}$ and the multiplication by $-t$,

$$F_{\text{est}}(t) = -\frac{6}{\tau^3}\int_{t-\tau}^{t} \left[(\tau - 2\sigma)y(\sigma) + \alpha\sigma(\tau - \sigma)u(\sigma)\right] d\sigma \tag{3}$$

2.3.2. Second approach. Close the loop with the iP (2):

$$F_{\text{est}}(t) = \frac{1}{\tau}\left[\int_{t-\tau}^{t} (\dot{y}^\star - \alpha u - K_P e)\, d\sigma\right] \tag{4}$$

Remark 2.2. Note the following facts:

- integrals (3) and (4) are low pass filters,
- $\tau > 0$ might be quite small,
- the integrals may of course be replaced in practice by classic digital filters.

Remark 2.3. A hardware implementation of the above computations is easy [27].

3. Modeling for computer simulations

Several authors (see, *e.g.*, [46]) 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.*, [4], [6], [44], [48], and the references therein). Like in [5], a linear model due to [15] is used:

$$\begin{cases} \dot{T}_{\text{int}} = & \frac{Q}{C_a} - \frac{K_c}{C_a}\left(T_{\text{int}} - T_{\text{wall}}\right) - \frac{K_f}{C_a}\left(T_{\text{int}} - T_{\text{ext}}\right) \\ \dot{T}_{\text{wall}} = & \frac{K_c}{C_w}\left(T_{\text{int}} - T_w\right) - \frac{K_{ext}}{C_a}\left(T_{\text{wall}} - T_{\text{ext}}\right) \end{cases} \tag{5}$$

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 [11]: $C_a = 1400$, $C_w = 2200$, $K_c = 1.4$, $K_f = 0.004$, $K_{ext} = 0.04$.

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

4. Comparisons of computer simulations

4.1. iP

Set $\alpha = 0.5$, $K_P = -0.5$ in Equation (2). It yields Figure 1 where the results are excellent with the 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 4.1. Lack of space prevents us from showing the excellent results obtained with values of the coefficients in Equation (5) 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.

4.2. PI

Introduce the classic proportional-integral (PI) controller (see, *e.g.*, [7]):

$$Q = k_p e + k_i \int e \tag{6}$$

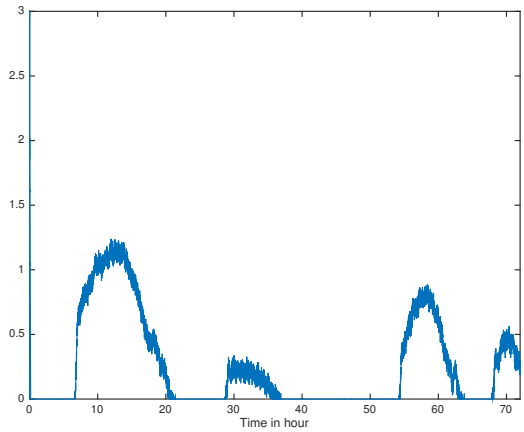
where

- $e = y - y^\star$ is the tracking error,
- $k_p, k_i \in \mathbb{R}$ are 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 4.1, Figures 4 and 1 become almost identical.

Remark 4.2. This result is not surprising. It is known [9], [18] that iPs and PIs are equivalent in some sense.

Remark 4.3. In order to avoid steps we could have also employed *setpoint ramping* (see, *e.g.*, [32]).



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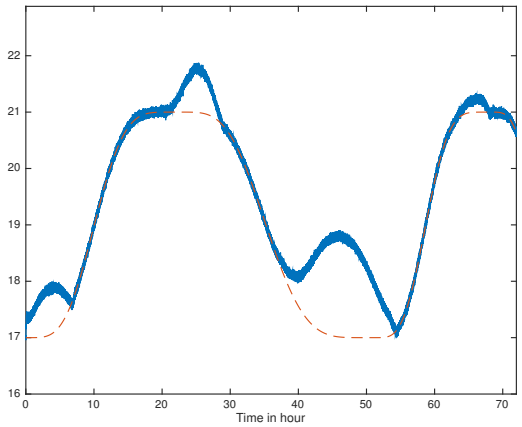

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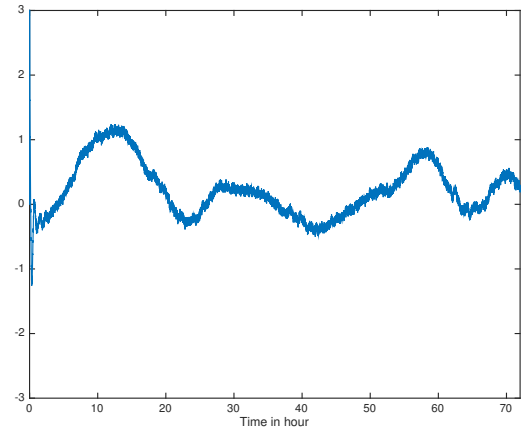
Figure 1. iP with heating



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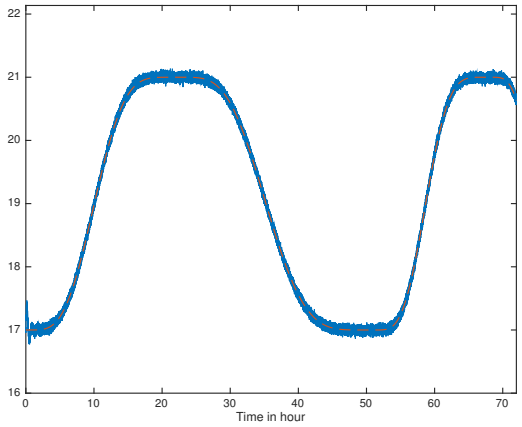


(b) Reference (- -) and temperature

Figure 2. iP with heating and cooling

4.3. Flatness-based predictive control

4.3.1. Generalities. Flatness-based control, which was introduced more than 25 years ago [20], certainly is one of the very few academic advances which have become popular in the industrial world (see also, *e.g.*, [7], [21], [39], [40], [49]). It might be viewed as another way of doing predictive control, but without any optimization techniques. From this standpoint, the first Equation in (5) yields

$$Q^\star = C_a \left(\dot{T}^\star_{\text{int}} + (\frac{K_c}{C_a} + \frac{K_f}{C_a}) T^\star_{\text{int}} \right)$$

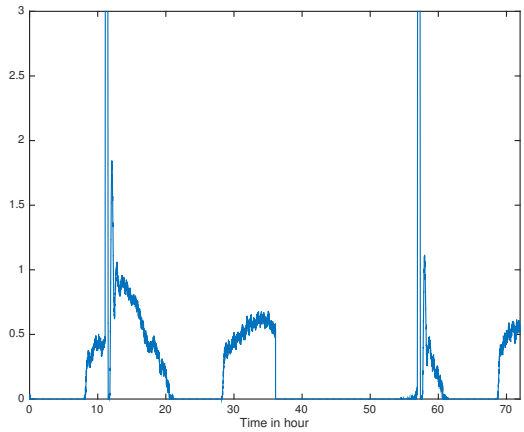
where $T^\star_{\text{int}}$ is the reference trajectory for the internal temperature and $Q^\star$ the corresponding open-loop control. The closed-loop control reads $Q = Q^\star + C(e)$, where $C(e)$ is some regulator.

4.3.2. 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 4.4. Let us add however that such a perturbation might be measured and therefore rejected via some appropriate tools (see, *e.g.*, [19]).[3]

4.3.3. PI. $C(e)$ is now a PI (6). 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

3. Such a control design is often called *Active Disturbance Rejection Control*, or *ADRC* (see, *e.g.*, [42] and the references therein).



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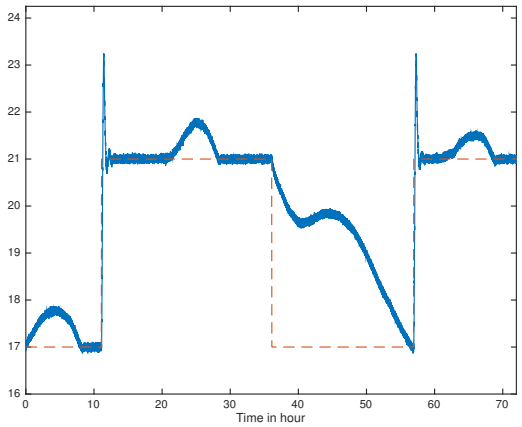

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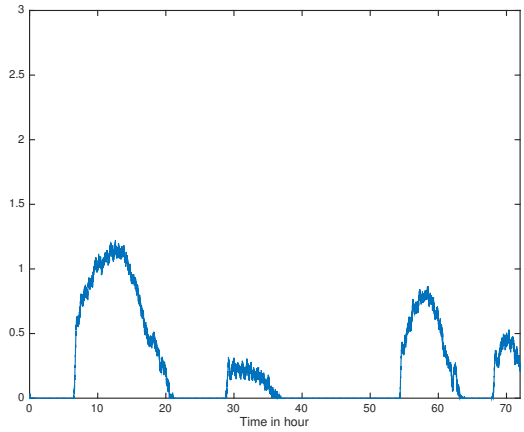
Figure 3. PI with steps



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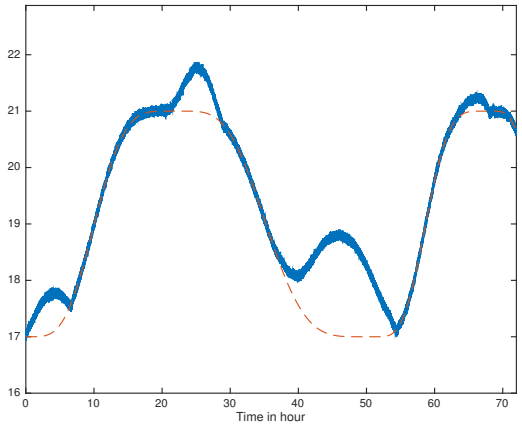

(b) Reference (- -) and temperature

Figure 4. PI with a smooth reference trajectory

comparison of performances displayed in Figure 7 and Figure 1 show a poor robustness with respect to noises.

Remark 4.5. Section 4.3 confirms that a model-based standpoint might be cumbersome and, therefore, inappropriate.

5. 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 on an experimental greenhouse [30] should make us optimistic.

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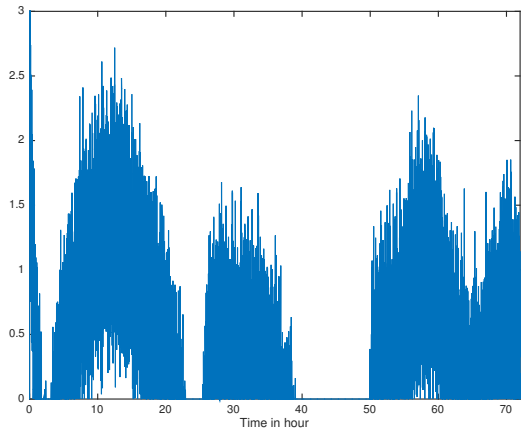

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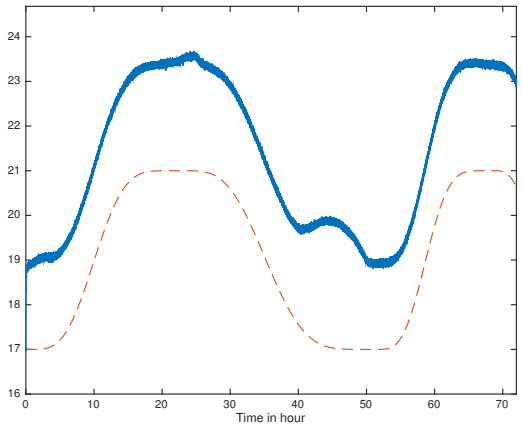

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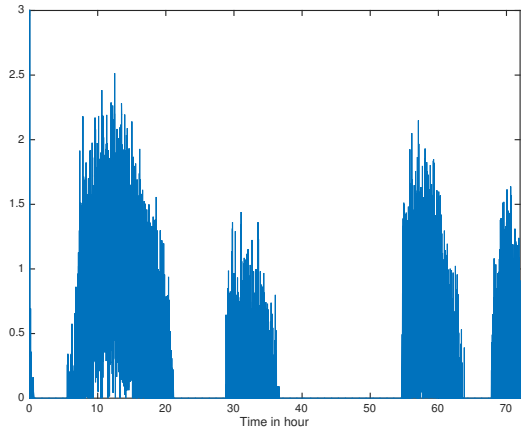
Figure 5. Flatness and P



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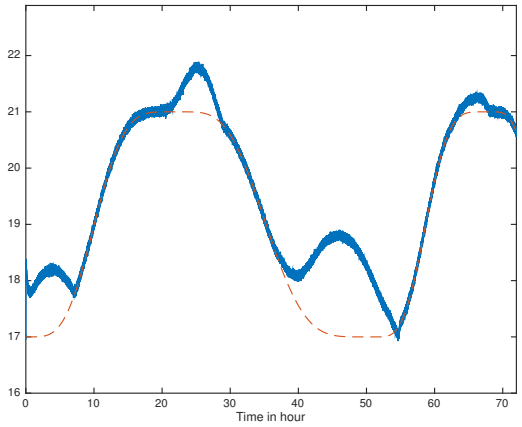

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Figure 6. Flatness and PI

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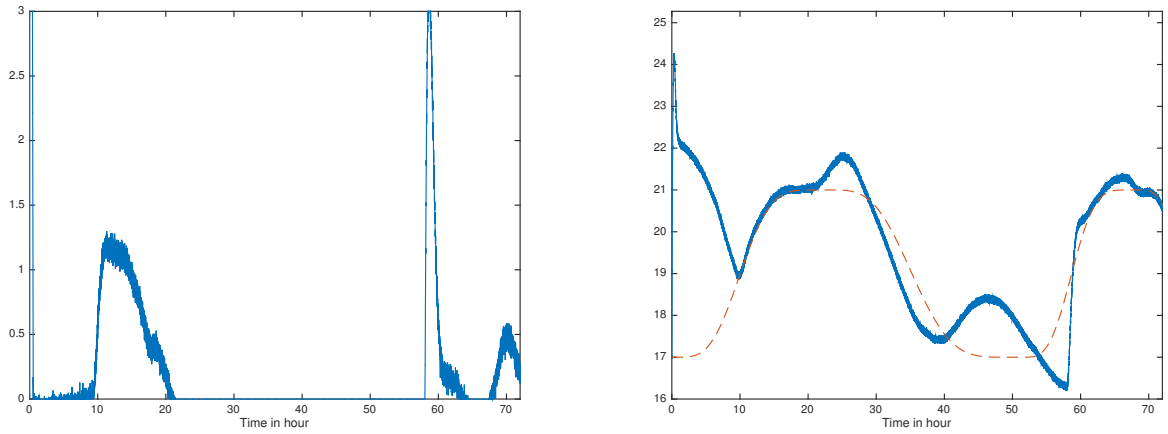

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Figure 7. Flatness and PI with "small" poles

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