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A model-free control strategy for an experimental greenhouse with an application to fault accommodation

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Abstract

Writing down mathematical models of agricultural greenhouses and regulating them via advanced controllers are challenging tasks since strong perturbations, like meteorological variations, have to be taken into account. This is why we are developing here a new model-free control approach and the corresponding “intelligent” controllers, where the need of a “good” model disappears. This setting, which has been introduced quite recently and is easy to implement, is already successful in many engineering domains. Tests on a concrete greenhouse and comparisons with Boolean controllers are reported. They not only demonstrate an excellent climate control, where the reference may be modified in a straightforward way, but also an efficient fault accommodation with respect to the actuators.

Keywords: Agriculture, greenhouse, temperature, hygrometry, model-free control, intelligent proportional controller, fault-tolerant control

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URL: <http://www.lsis.org> (Frédéric Lafont)

Table 1: Percentage distribution of surfaces for the soilless crop greenhouses in France in 2005

Climate control			
Without	Manual	Automated	Computerized
6 %	7 %	20 %	67 %

1 **1. Introduction**

2 Table 1 in Callais (2006) shows that already a few years ago a large per-
3 centage of agricultural greenhouses were computerized. The corresponding au-
4 tomated microclimate regulation should not only improve the production and
5 its quality but also reduce pollution and energy consumption. Most of the ex-
6 isting control approaches, like adaptive control, predictive control, optimal con-
7 trol, stochastic control, nonlinear control, infinite dimensional systems, PIDs,
8 On/Off, or Boolean, control, fuzzy control, neural networks, soft computing,
9 expert systems, . . . , have been employed and tested. The literature on the
10 modeling and control of greenhouses is therefore huge. See, *e.g.*:

- 11 • the books by Medjber (2012); Ponce *et al.* (2012); Rodríguez *et al.* (2015);
12 van Straten *et al.* (2010); Urban *et al.* (2010); Von Zabeltitz (2011); and
13 the references therein,
- 14 • the papers and memoirs by Aaslyng *et al.* (2005); Arvantis *et al.* (2000);
15 Balmat, Lafont (2003); Bennis *et al.* (2008); Blasco *et al.* (2007); Caponetto *et al.*
16 (2000); Cate, Challa (1984); Critten, Bailey (2002); Cunha *et al.* (1997);
17 Dong *et al.* (2013); Duarte-Galvan *et al.* (2012); El Ghomari *et al.* (2005);
18 Fourati (2014); Gruber *et al.* (2011); Ioslovich *et al.* (2009); Kimball (1973);
19 Kittas, Batzanas (2010); Lafont, Balmat (2002); Pasgianos *et al.* (2003);
20 Pessel, Balmat (2005); Pessel *et al.* (2009); Piñón *et al.* (2005); Salgado, Cunha
21 (2005); Shamshiri, Wan Ismail (2013); Speetjens *et al.* (2009); Tchamitchian *et al.*
22 (2006); Viard-Gaudin (1981); Zhang (2008); and the references therein.

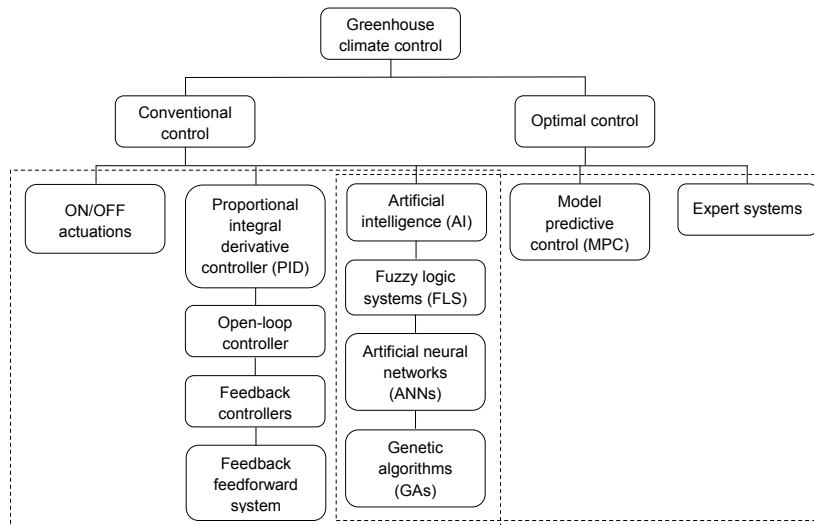


Figure 1: Greenhouse control theories classification in Duarte-Galvan *et al.* (2012)

23 Let us summarize, perhaps too briefly, some of the various control aspects which
 24 were developed in the above references (see, also, Figure 1):

- 25 • writing down a “good” model, which is necessarily nonlinear, either via
 26 physical laws or via black box identification, leads to most severe cali-
 27 bration and robustness issues, especially with respect to strong weather
 28 disturbances, which are impossible to forecast precisely,
- 29 • for multi-models appropriate control laws are difficult to synthesize,
- 30 • “conventional” PID and On/Off techniques, which preclude any math-
 31 ematical modeling, are therefore the most popular in industrial green-
 32 houses, although:
 - 33 – they are difficult to tune,
 - 34 – their performances are far from being entirely satisfactory.

35 Here, an experimental greenhouse is regulated via a new approach, called
 36 *model-free control* (Fliess, Join (2013)), and their corresponding *intelligent* con-
 37 trollers, where:

- 38 • any need of a mathematical model disappears,
- 39 • the flaws of conventional PID and On/Off techniques vanish.

40 It should be emphasized that this setting (which is less than ten years old):

- 41 • has already been most successfully applied in a number of practical case-
42 studies, which cover a large variety of domains (see the references in
43 Fliess, Join (2013, 2014)),
- 44 • is easy to implement (Fliess, Join (2013); Join *et al.* (2013)).

45 Besides excellent experimental results, a straightforward fault tolerant control
46 with respect to actuators is a quite exciting byproduct. It should be emphasized
47 here that fault accommodation for greenhouse control has unfortunately not
48 been very much investigated until now (see nevertheless Bontsema *et al.* (2011)).

49 Our paper is organized as follows. Sections 2 and 3 summarize respectively
50 model-free control and actuator fault accommodation. Our experimental green-
51 house system and its climate management problem are described in Section 4.
52 Section 5 displays our experimental results with our very simple intelligent con-
53 troller. Comparisons with a classical Boolean controller are found in Section 6.
54 The efficiency of our method, is further confirmed in Section 7 where the tem-
55 perature references are modified. Section 8 deals with fault accommodation.
56 Some concluding remarks are provided in Section 9.

57 When compared to the two first drafts of this work, which appeared in
58 conferences (Lafont *et al.* (2013, 2014)), this paper:

- 59 • is proposing a much simpler control synthesis than in Lafont *et al.* (2013),
- 60 • gives a much more detailed review of model-free control than in Lafont *et al.*
61 (2013, 2014),
- 62 • reports, contrarily to Lafont *et al.* (2013, 2014):
 - 63 – the hygrometry control,
 - 64 – the time evolution of F in Equation (1).

65 **2. Model-free control and intelligent controllers¹**

66 *2.1. The ultra-local model*

For the sake of notational simplicity, let us restrict ourselves to single-input single-output (SISO) systems.² The unknown global description of the plant is replaced by the *ultra-local model*:

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

67 where:

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

72 The following comments might be useful:

- 73 • Equation (1) is only valid during a short time lapse. It must be continu-
- 74 ously updated,³
- 75 • F is estimated via the knowledge of the control and output variables u
- 76 and y ,
- 77 • F subsumes not only the unknown structure of the system, which most of
- 78 the time will be nonlinear, but also of any disturbance.⁴

¹See Fliess, Join (2013) for more details.

²See also Section 5.

³The following comparison with computer graphics, which is extracted from Fliess, Join (2013), might be enlightening. Reproducing on a screen a complex plane curve is not achieved via the equations defining that curve but by approximating it with short straight line segments. Equation (1) might be viewed as a kind of analogue of such a short segment.

⁴See also the recent comments by Gao (2014).

Remark 2.1. *The general ultra-local model reads*

$$y^{(\nu)} = F + \alpha u$$

79 where $y^{(\nu)}$ is the derivative of order $\nu \geq 1$ of y . When compared to Equation (1),
 80 the only concrete case-study where such an extension was until now needed, with
 81 $\nu = 2$, has been provided by a magnetic bearing (see De Miras et al. (2013)).
 82 This is explained by a very low friction (see Fliess, Join (2013)).

83 2.2. Intelligent controllers

Close the loop with the following *intelligent proportional-integral controller*,
 or *iPI*,⁵

$$u = -\frac{F - \dot{y}^* + K_P e + K_I \int e}{\alpha} \quad (2)$$

84 where:

- 85 • $e = y - y^*$ is the tracking error,
- 86 • K_P, K_I are the usual tuning gains.

When $K_I = 0$, we obtain *intelligent proportional controller*, or *iP*, which will be
 employed here:

$$\boxed{u = -\frac{F - \dot{y}^* + K_P e}{\alpha}} \quad (3)$$

Combining Equations (1) and (3) yields:

$$\dot{e} + K_P e = 0$$

87 where F does not appear anymore. The tuning of K_P is therefore quite straight-
 88 forward. This is a major benefit when compared to the tuning of “classic”
 89 PIDs (see, e.g., Åstrom, Hägglund (2006); O’Dwyer (2009), and the references
 90 therein). Note moreover that, according to Section 6.1 in Fliess, Join (2013),
 91 our iP is equivalent in some sense to a classic PI controller. The integral term

⁵The term *intelligent* is borrowed from Fliess, Join (2013), and from earlier papers which are cited there.

92 in the PI controllers explains why steady state errors are avoided here with our
93 iP.

94 **Remark 2.2.** *Section 6 in Fliess, Join (2013) extends the above equivalence*
95 *to classic PIDs and the “intelligent” controllers of Fliess, Join (2013). Two*
96 *important facts, which were quite mysterious in today’s literature, are therefore*
97 *fully clarified:*

- 98 • *the strange ubiquity of PIDs in most diverse engineering situations,*
- 99 • *the difficulty of a “good” PID tuning for concrete industrial plants.*

100 **Remark 2.3.** *Besides numerous academic comparisons in Fliess, Join (2013),*
101 *see, e.g., Gédouin et al. (2011) for a thorough comparison between our intelli-*
102 *gent controllers and PIDs for a concrete case-study, i.e., the position control of*
103 *a shape memory alloy active spring. All those comparisons turn out to be in*
104 *favor of our intelligent controllers.*

105 **Remark 2.4.** *Our intelligent controllers are successfully used in an on-off way.*
106 *This was also the case in Abouaissa et al. (2012) for a freeway ramp metering*
107 *control.*

108 2.3. Estimation of F

109 Assume that F in Equation (1) is “well” approximated by a piecewise con-
110 stant function F_{est} . The estimation techniques below are borrowed from Fliess, Sira-Ramírez
111 (2003, 2008).⁶

112 2.3.1. First approach

Rewrite then Equation (1) in the operational domain (see, e.g., Yosida
(1984)):

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

⁶See also the excellent recent book by Sira-Ramírez *et al.* (2014).

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 $-t$,

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

113 where $\tau > 0$ might be quite small. This integral, which is a low pass filter, may
114 of course be replaced in practice by a classic digital filter.

115 2.3.2. Second approach

Close the loop with the iP (3). It yields:

$$F_{\text{est}}(t) = \frac{1}{\tau} \left[\int_{t-\tau}^t (iy^* - \alpha u - K_P e) d\sigma \right]$$

116 **Remark 2.5.** *It should be emphasized that the above estimation of the func-*
117 *tion F in Equation (1) is quite different from model-based parameter identifica-*
118 *tion. This remains valid in a control adaptive setting, where, as stated by, e.g.,*
119 *Landau et al. (2011), “one needs to know the dynamic model of the plant to be*
120 *controlled.”*

121 **Remark 2.6.** *Implementing our intelligent controllers is easy (see Fliess, Join*
122 *(2013); Join et al. (2013)).*

123 3. Actuator’s fault accommodation

124 As explained in Figure 2 there are two main ways in order to deal with an
125 actuator fault (see, e.g., Isermann (2011); Noura *et al.* (2009); Shumsky *et al.*
126 (2011)):

- 127 1. the first one is self-tuning, or fault accommodation. It relies on an on-line
128 control law that preserves the main performances, while some minor parts
129 may slightly deteriorate,

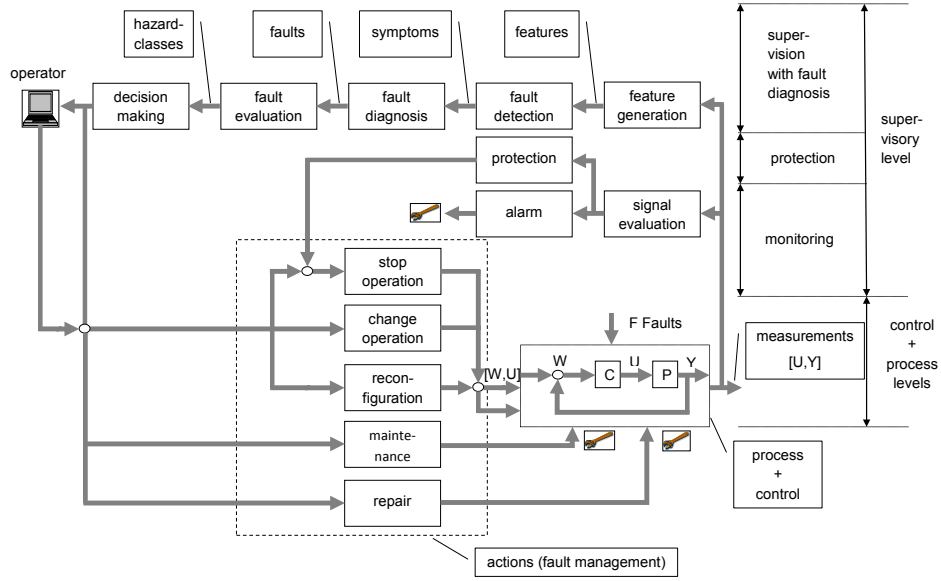


Figure 2: A supervision structure

130 2. the second one is self-organization where faulty components are replaced.
 131 We only consider here fault accommodation. The computations below are
 132 adapted from Fliess, Join (2013).

Express the actuator fault via

$$u_r = u(1 - \beta) \quad (4)$$

133 where:

- 134 • β , $0 < \beta < 1$, is the loss of efficiency of the actuator,
- 135 • u_r is the true control variable.

136 The two following cases are not considered:

- 137 • $\beta = 0$ means that there is no fault,
- 138 • $\beta = 1$ implies that the control does not act anymore.

Then Equation (1) becomes

$$\dot{y} = \bar{F} + \alpha u$$

where

$$\bar{F} = F - \alpha\beta u$$

139 The fault accommodation is then achieved by estimating \bar{F} as in Section 2.3.

140 **Remark 3.1.** *It is obvious that β does not need to be:*

- 141 • *a constant and may be time-varying,*
- 142 • *known in order to carry on the above computations.*

143 **Remark 3.2.** *For model-based diagnosis, estimation techniques stemming from*
144 *Fliess, Sira-Ramírez (2003, 2008) have already lead to quite important advances.*
145 *See, e.g., Fliess et al. (2004, 2008); Kiltz et al. (2014); Villagra et al. (2011a,b).*

146 4. Greenhouse climate management

147 Figure 3 shows our experimental plastic greenhouse which is manufactured
148 by the French company *Richel*. Its area is equal to 80 m². It is the property of
149 the *Laboratoire des Sciences de l'Information et des Systèmes (LSIS)*, to which
150 the first three authors belong. This laboratory is located at the *Université de*
151 *Toulon* in the south of France. Our experimental greenhouse is controlled by
152 a microcomputer and interfaced with the FieldPoint FP-2000 network module
153 developed by the American company *National Instruments Corporation*. The
154 FP-2000 network module is associated with two analog input modules (FP-AI-
155 110, FP-AI-111), for the acquisition, and two relay output modules (FP-RLY-
156 420), for the control. The acquisition and control system is developed with the
157 *LabView* language. The sampling period is equal to 1 minute. The inside air
158 temperature and the humidity are controlled.

159 4.1. Description of the system

160 The greenhouse is a multi-input and multi-output (MIMO) system which is
161 equipped with several sensors and actuators (Figure 4).

162

163 There are:



Figure 3: Our experimental greenhouse system

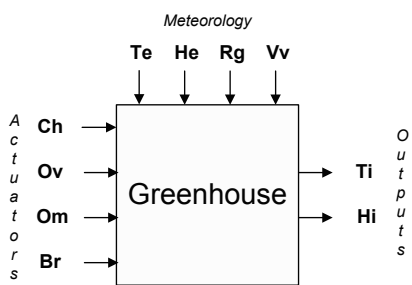


Figure 4: System variables

- 164 • four actuators:
 - 165 1. Heating (thermal power 58 kw): Ch (*Boolean*),
 - 166 2. Opening (50 % max): Ov (%),
 - 167 3. Shade: Om (%),
 - 168 4. Fog system: Br (*Boolean*).

- 169 • four meteorological disturbance sensors:
 - 170 1. External temperature: Te ($^{\circ}C$),
 - 171 2. External hygrometry: He (%),
 - 172 3. Solar Radiation: Rg (W/m^2),
 - 173 4. Wind speed: Vv (km/h).

- 174 • two internal climate sensors:
 - 175 1. Internal temperature: Ti ($^{\circ}C$),
 - 176 2. Internal hygrometry: Hi (%).
- 177

178 This system is nonstationary and strongly disturbed. Figures 5 and 6 show, for
179 instance, quite high solar radiation and external temperature during the 24th
180 September 2014. These meteorological conditions have a significant effect on
181 the inside greenhouse climate which are clear on Figure 7.

182 4.2. Climate management problem

183 The management of the greenhouse climate aims to maintain simultaneously
184 a set of climatic factors such as the temperature, the hygrometry, and the rate
185 of CO_2 ⁷ close to their respective references. In our greenhouse, the tempera-
186 ture and the hygrometry managements are treated together, because these two
187 quantities are strongly correlated:

- 188 • the heating has a dehumidifier effect,

⁷This last rate is not available on our greenhouse.

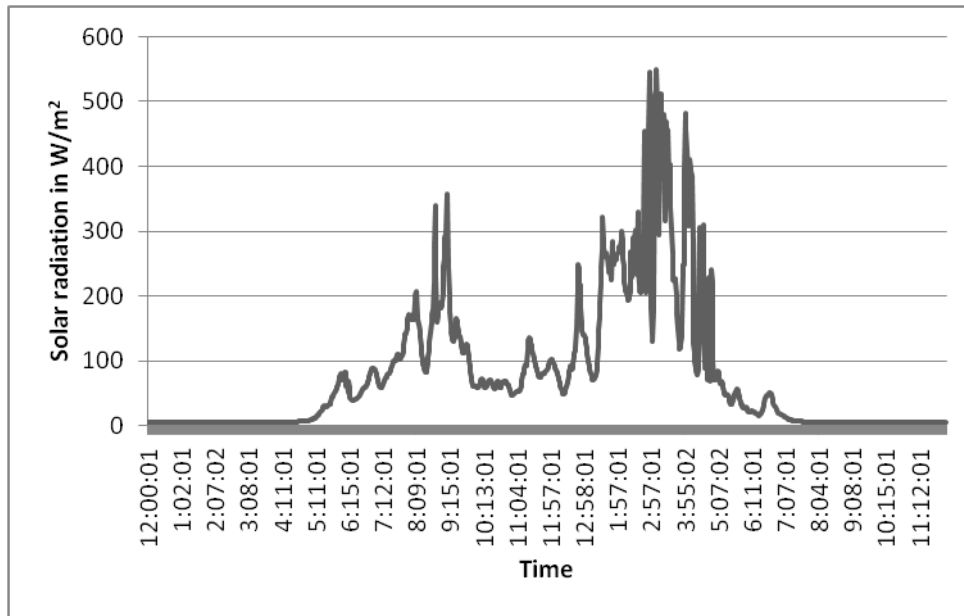


Figure 5: Solar radiation during the 24th September, 2014

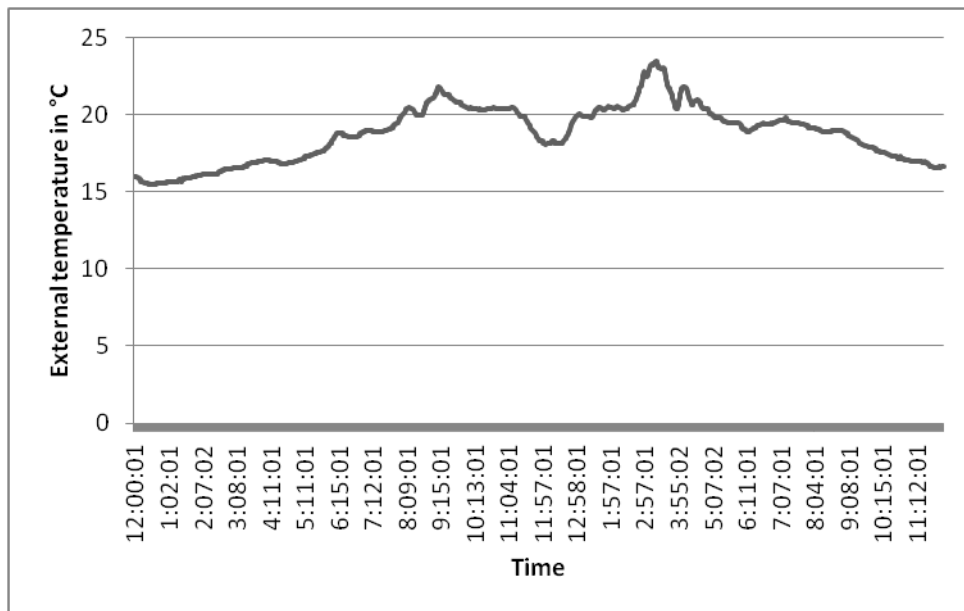


Figure 6: External temperature during the 24th September, 2014

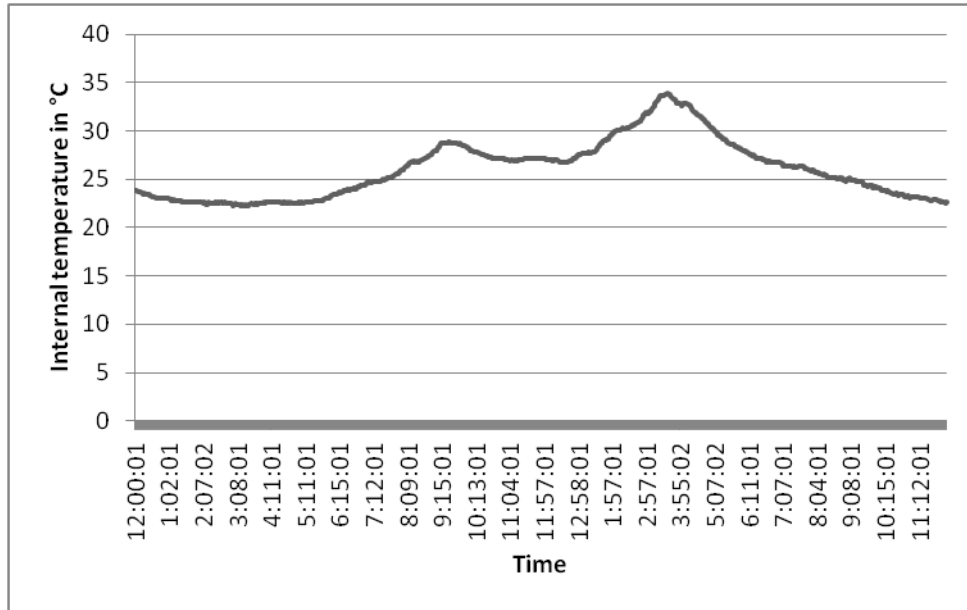


Figure 7: Internal temperature during the 24th September, 2014

- 189 • the opening system has a cooling and dehumidifier effect,
- 190 • the fog system has a cooling effect.

191 Controlling the temperature and the hygrometry is therefore of utmost impor-
 192 tance. In order to choose the suitable output references, two main strategies
 193 exist.

194 *4.2.1. The classic strategy*

195 Growers refer to their knowledge to fix the hygrometry and temperature
 196 references.

197 *Hygrometry reference.* There is no real recommendations by species. It appears
 198 nevertheless that:

- 199 • for the multiplication phase, the hygrometry must be greater than 80 %,
- 200 • for the growth phase, the reference is comprised between 60 and 80 %,

201 • for the tomato, the reference is rather comprised between 50 and 70 %.

202

203 Let us mention some other advices. Avoid:

204 • condensations,

205 • a humidity level close to saturation (100 %),

206 • a humidity level below 40 % for seedlings,

207 • absolutely a hygrometry below 20 %.

208 *Temperature reference.* Table 2 displays references among suppliers, which are
209 based on the species.⁸ Observe that the difficulties for tuning an efficient con-
210 troller may be attributed to the following causes:

211 • various references:

212 – in a day,

213 – according to the species.

214 • system parameter variations according to the plant growth.

215

216 4.2.2. *The innovative strategy*

217 Tchamitchian *et al.* (2006) developed a decision-making system, called SER-
218 RISTE. It generates daily climate reference for greenhouse grown tomatoes.
219 This system, which uses the knowledge of advisers or expert growers to manage
220 the greenhouse climate, can be encapsulated and exploited in a reference de-
221 termination software. This tool provides daily references to growers taking into
222 account various objectives such as the phytosanitary prevention, the energetic
223 cost, the growth of the crop, The system uses data such as seasons, crop
224 stages, the daily period (divided into three subperiods), the characteristics of

⁸Temperatures are expressed in Celsius degrees.

Table 2: Temperature reference (see (Urban *et al.*, 2010))

Species	Night reference	Day reference	Remarks
Aubergine	21°C	22°C	During 4 weeks after the plant.
	19°C	21°C	To the end
Cucumber	21°C	23°C	During 4 weeks After the plant.
	20°C	22°C	During the next 6 weeks.
	19°C	21°C	To the end.
Lettuce	10°C	10°C	During 2 weeks After the plant.
	6°C	12°C	To the end.
Pepper	20°C	23°C	During 3 weeks after the plant.
	18°C	22°C	To the end.
Tomato	20°C	20°C	During 1 week after the plant.
	18.5°C	19.5°C	During the next 5 weeks.
	17.5°C	18.5°C	To the end.
Azalea	18/21°C	>18°C	
Chrysanthemum	17°C	18°C	
Gerbera	13/15°C		
Antirrhinum	10/11°C		
Carnation	12/13°C	18°C	
Rosebush	17°C	21°C	

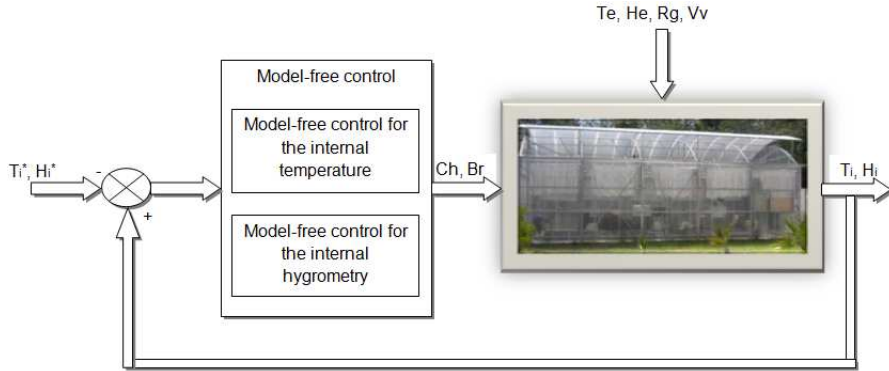


Figure 8: Block diagram of the experimental setup

225 the greenhouse system (location, heating system, ...) and dynamic informations
 226 (past climate, crop state, ...). Sections 4.2.1 and 4.2.2 show the reference changes
 227 according to the time of day or the plant growth. This is another justification
 228 for our model-free control.

229 5. Intelligent P control of the experimental greenhouse

230 An iP (3) is implemented for the regulation of the temperature and the
 231 hygrometry, which turn out to be naturally decoupled in our model-free setting
 232 (Figure 8).⁹

233 We are estimating F via the technique sketched in Section 2.3.2.

234 5.1. Estimation of F

The estimation $F_{\text{est}}^{\text{temp}}$ is given by

$$F_{\text{est}}^{\text{temp}} = \frac{1}{\delta} \int_{T-\delta}^T \left(-\alpha Ch + \dot{T}i^* - K_P e_{T_i} \right) d\tau \quad (5)$$

235 where:

⁹Our restriction in Section 2 to detail only SISO systems is therefore fully justified. See also Menhour *et al.* (2013) for the behavior of a vehicle.

Table 3: Setting values

Variable	Value
δ	6 minutes
α	1
K_P	2

- 236 • $e_{Ti} = Ti - Ti^*$ is the temperature tracking error,
- 237 • $\dot{T}i^*$ is the reference derivative of Ti (when internal temperature reference
- 238 is constant then $\dot{T}i^*$ is equal to 0).

and $F_{\text{est}}^{\text{hygro}}$ by

$$F_{\text{est}}^{\text{hygro}} = \frac{1}{\delta} \int_{T-\delta}^T \left(-\alpha Br + \dot{H}i^* - K_P e_{Hi} \right) d\tau \quad (6)$$

239 where:

- 240 • $e_{Hi} = Hi - Hi^*$ is the temperature tracking error,
- 241 • $\dot{H}i^*$ is the reference derivative of Hi (when internal hygrometry reference
- 242 is constant then $\dot{H}i^*$ is equal to 0).

243 5.2. Setting values and results

244 The controllers Ch and Br are deduced from Equations (1), (3) and (5).
 245 They are *Pulse Width Modulation (PWM)* controllers. The rules given in Sec-
 246 tion 2.1 yield Table 3, which displays the same values for the two controllers.

247 The reference output is $18^\circ C$ for the temperature with a tolerance equal to
 248 $0.5^\circ C$ and 60 % for the hygrometry. The temperature sensors PT100 sensors,
 249 of class A, with an accuracy of $\pm 0.3^\circ C$. A tolerance of $0.5^\circ C$ would be realistic
 250 since, for many species, the difference between night and day reference is equal
 251 to $1^\circ C$, as shown in Table 2. We want to differentiate night and day. Sensors
 252 with an accuracy of $\pm 0.3^\circ C$ permit to take into account a tolerance equal to
 253 $0.5^\circ C$. Simulations last 12 hours, from 8:00 p.m. until 8:00 a.m. We choose

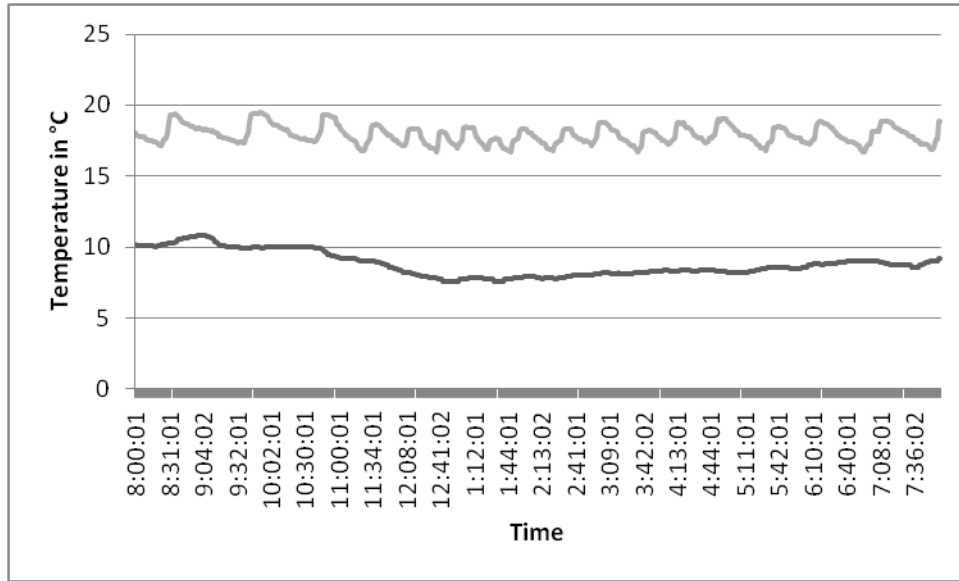


Figure 9: Temperature with model-free control (Te: black line - Ti: grey line)

254 the night in order to compare the obtained results with Boolean control (see
 255 Section 6) in similar weather conditions.

256 Figure 9 shows the internal/external temperature evolution during the night
 257 of 20-21 February 2014. Figure 10 shows the heating control sequences. Observe
 258 that the heating control allows at the internal temperature T_i to be close to its
 259 reference output. Figure 11 shows the evolution of F_{est}^{temp} during this night.

260 Figure 12 shows the internal hygrometry evolution during the night of 20-
 261 21 February 2014. Figure 13 shows the sequences for the fog control. We can
 262 observe that, at 4:00 a.m., the internal hygrometry H_i is also above the reference
 263 output: it started to rain. So, the fog system Br stops. Otherwise, the internal
 264 hygrometry H_i is close to this reference output.

265 Table 4 shows the mean and the variance of the error between T_i and the
 266 output reference of T_i and between H_i and the reference output of H_i .

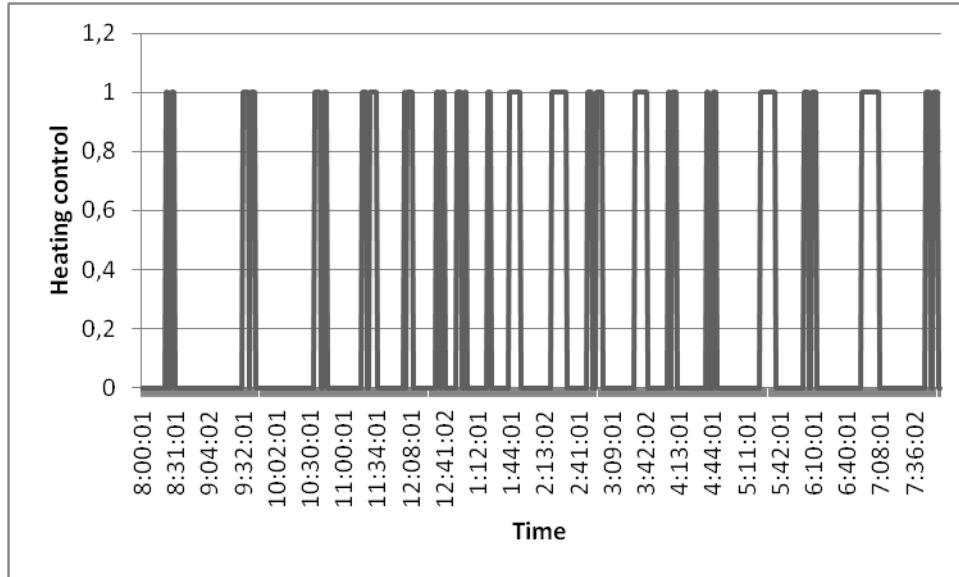


Figure 10: Heating control with model-free control

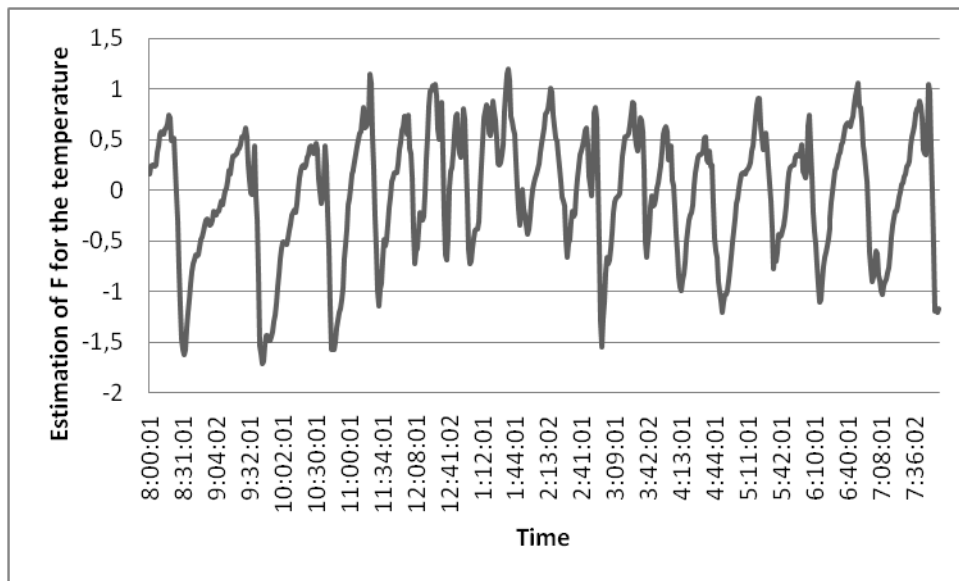


Figure 11: Evolution of F_{est}^{temp}

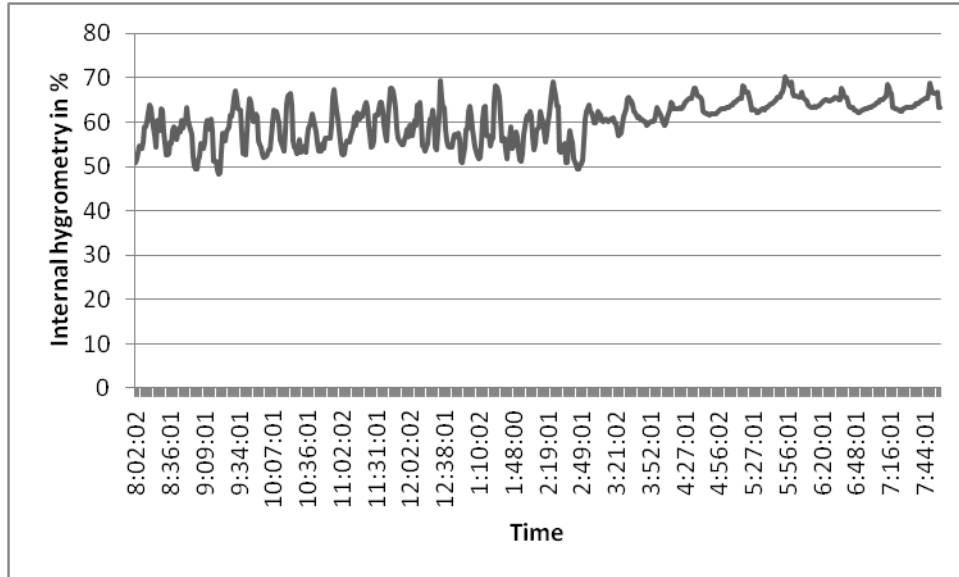


Figure 12: Internal hygrometry with model-free control

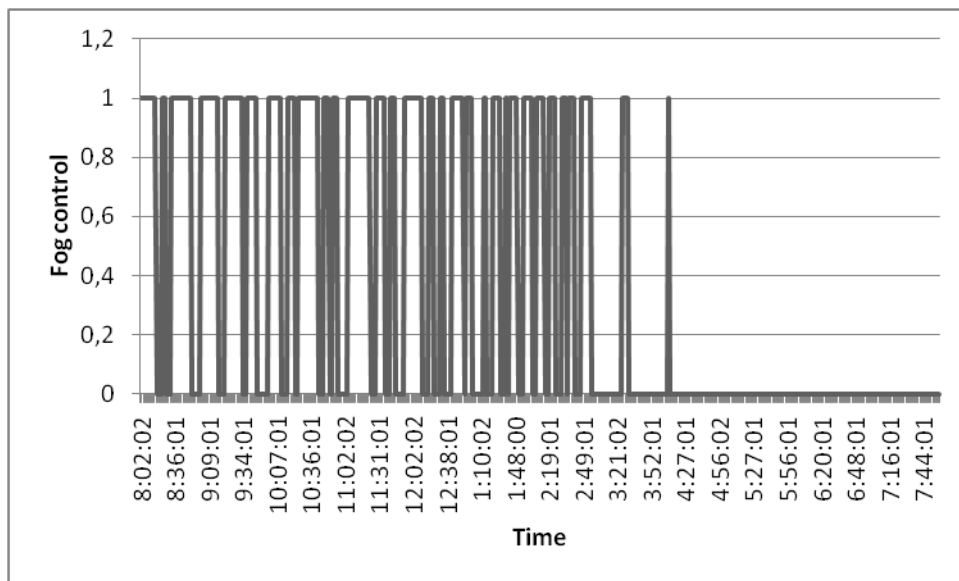


Figure 13: Fog control with model-free control

Table 4: Results evaluation for the model-free control

Output error	mean	variance
e_{T_i}	$-0.1^{\circ}C$	$0.4^{\circ}C$
e_{H_i}	0.4 %	21.8 %

Table 5: Results evaluation with a classic Boolean control

Output error	mean	variance
e_{T_i}	$0.8^{\circ}C$	$0.7^{\circ}C$
e_{H_i}	5.0 %	71.7 %

267 **6. Comparison between iP and classic Boolean control**

268 A classic Boolean control law with thresholds is employed for the compar-
 269 isons. This type of technique is quite often utilized in agriculture. Experiments
 270 have been carried on during two different nights, *i.e.*, 20 -21 and 21-22 February
 271 2014, respectively for the model-free and boolean settings. The temperature ref-
 272 erence output is $18^{\circ}C$ with a tolerance equal to $0.5^{\circ}C$, as in Section 5. For the
 273 hygrometry, a dehumidification reference should be selected. The fog control is
 274 periodic (3 minutes on and 27 minutes off) whatever the internal hygrometry.
 275 This Boolean control of the humidity is based on the grower rules. The dehu-
 276 midification reference allows to set the desired maximum hygrometry inside the
 277 greenhouse. In this test, we choose 60 %.

278 Figure 14 and 15 show respectively results for the internal temperature and
 279 for the heating control during the night of 21-22 February 2014.

280 Figure 16 shows the internal hygrometry evolution during the night of 21-22
 281 February 2014. Figure 17 shows the sequences for the fog control.

282 Table 5 shows the mean and the variance of the error between T_i and the
 283 output reference of T_i for this night.

284 Tables 4 and 5 demonstrate that our model-free control strategy behaves

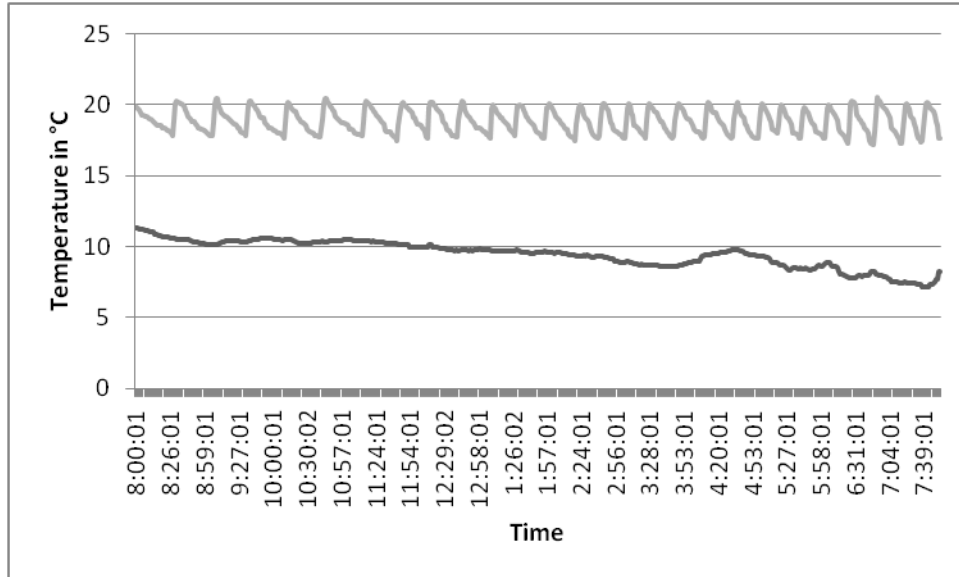


Figure 14: Temperature with a Boolean controller (Te: Black line - Ti: Grey line)

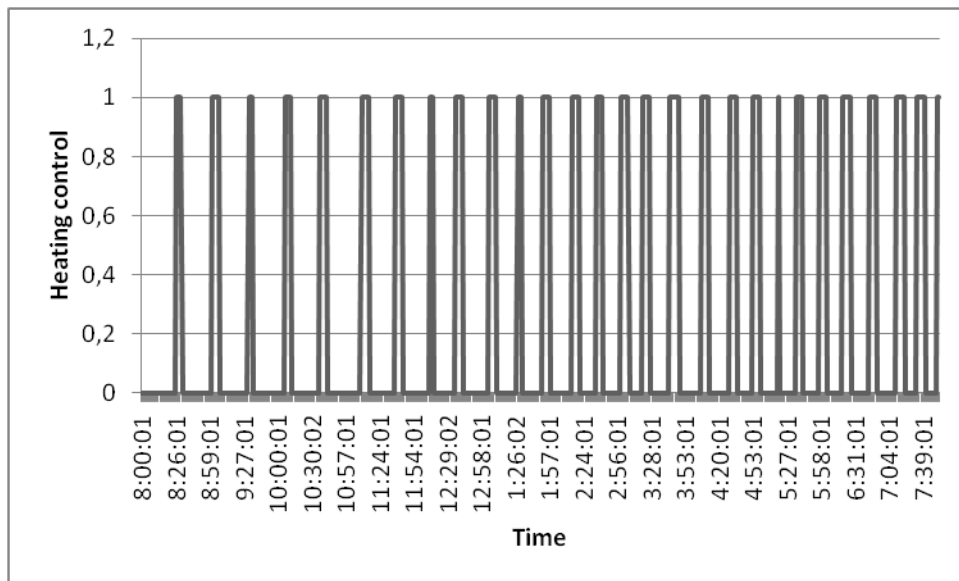


Figure 15: Heating control with a Boolean controller

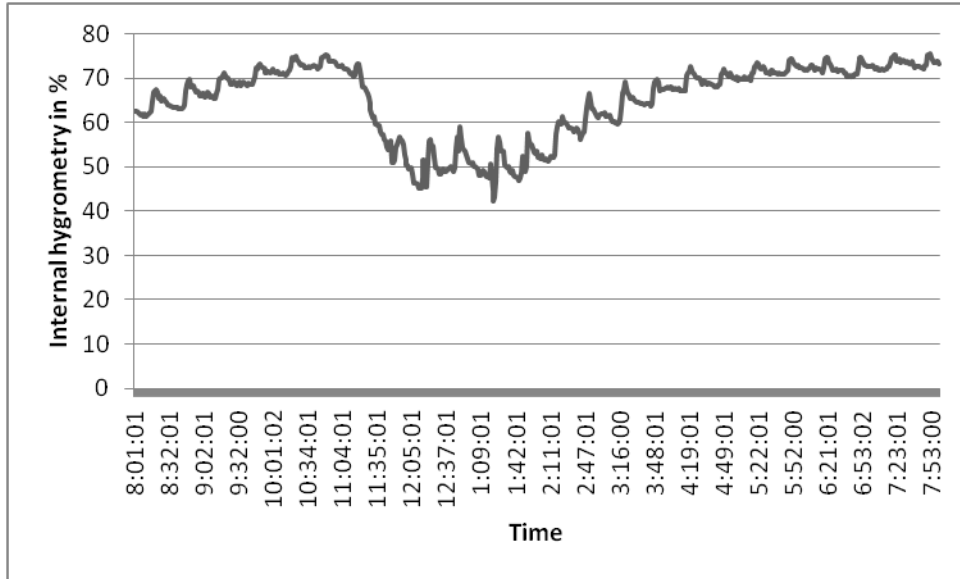


Figure 16: Internal hygrometry with a Boolean controller

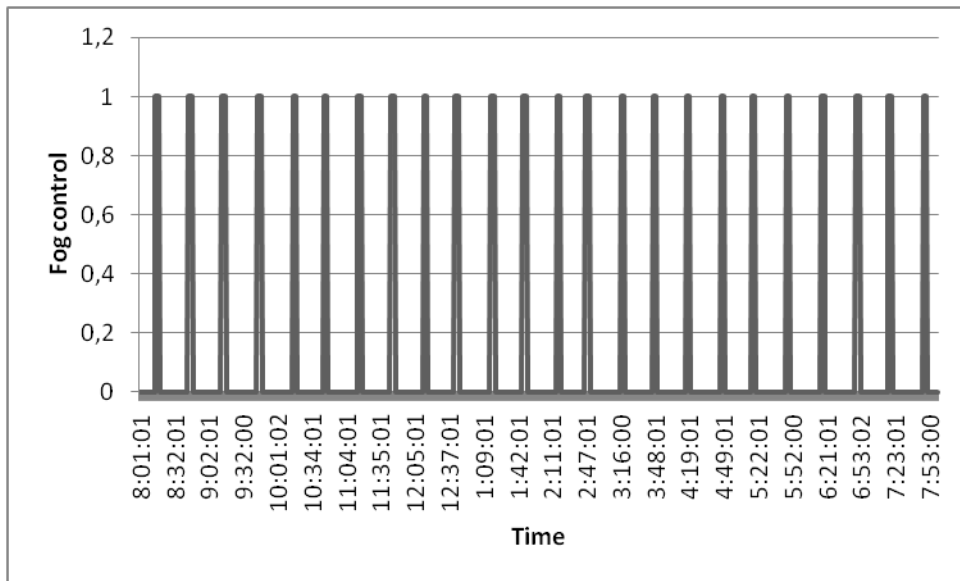


Figure 17: Fog control with a Boolean controller

Table 6: Comparisons of the energy

Actuator	Model-free control	Classical Boolean control
<i>Heat</i>	143 <i>min</i>	145 <i>min</i>

285 better than its Boolean counterpart. Let us emphasize two more points:

- 286 • as already explained in Section 4, one of the goals of climate control is to
287 consume as little energy as possible. Table 6 shows that the heating is on
288 only during 20 % of the time with the model-free setting. The model-free
289 controller is therefore much cheaper,
- 290 • for a given operating time, the model-free control ensures a better tracking
291 of the reference signal.

292 7. Reference change

293 Figure 18 shows results for the internal temperature with a reference change
294 (without any modification of the parameter values of the iP controller). We
295 regulate the greenhouse with the temperature reference output equal to $20^{\circ}C$
296 during the night of 11-12 February 2014. Figure 19 represents the heating
297 control.

298 Results for the internal temperature with an other reference change are dis-
299 played on Figure 20. We regulate the greenhouse with the temperature reference
300 output equal to $16^{\circ}C$ during the night of 17-18 February 2014. Figure 21 rep-
301 represents the heating control.

302 We can observe that model-free control results are always *good* since the
303 internal temperature follow to the reference output (see Table 7). As sketched
304 in Section 4.2 and presented in Table 2, this is a most significant advance.

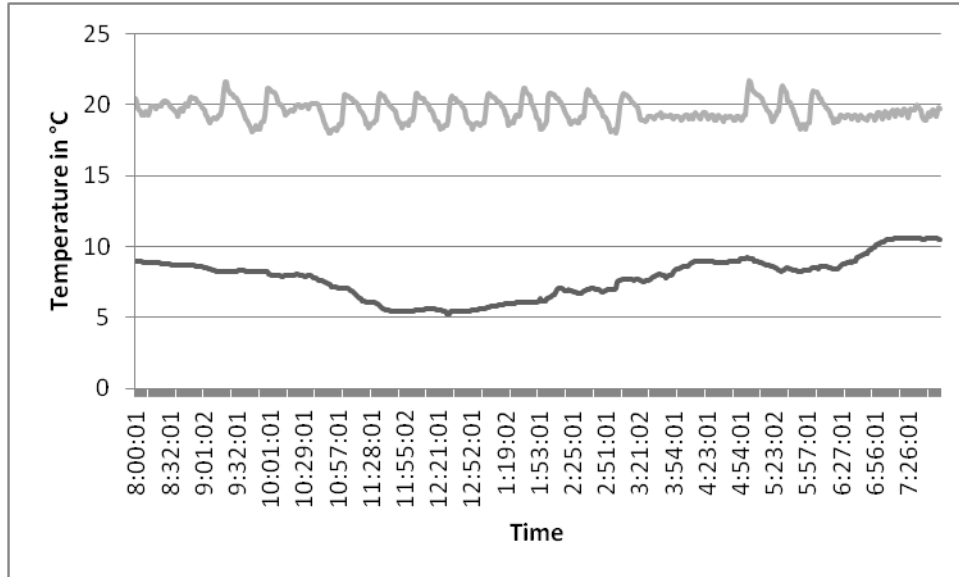


Figure 18: Temperature with model-free control (Te: Black line - Ti: Grey line)

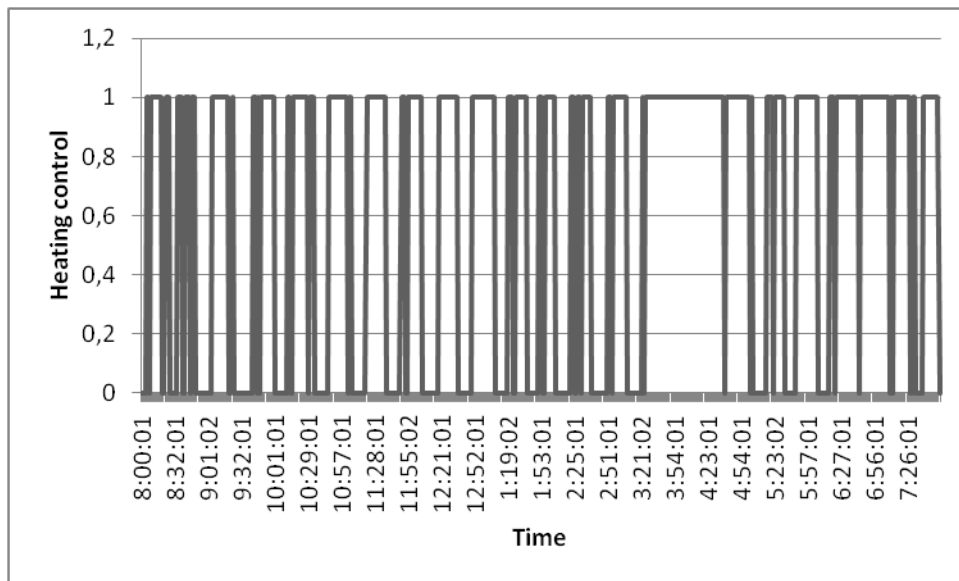


Figure 19: Heating control with model-free control

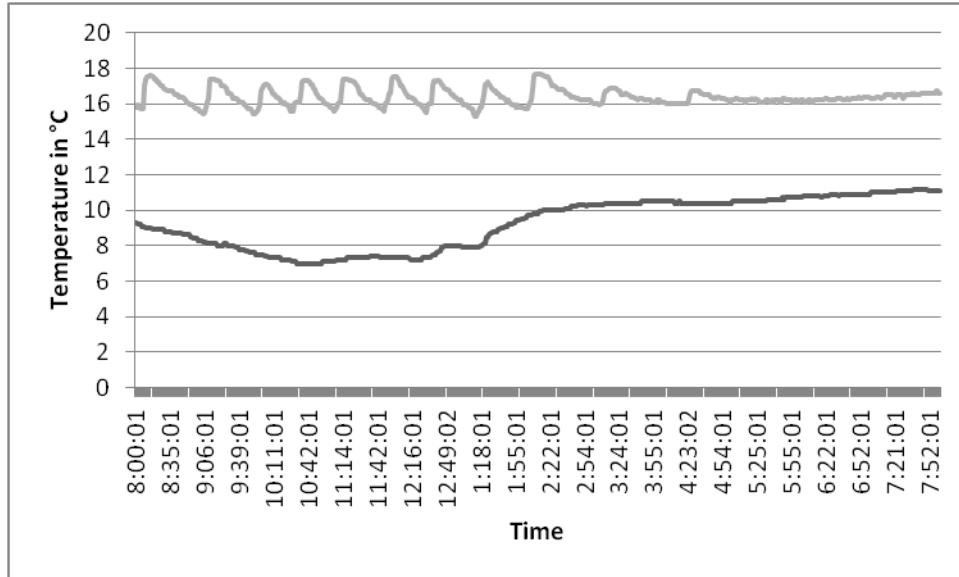


Figure 20: Temperature with model-free control (Te: Black line - Ti: Grey line)

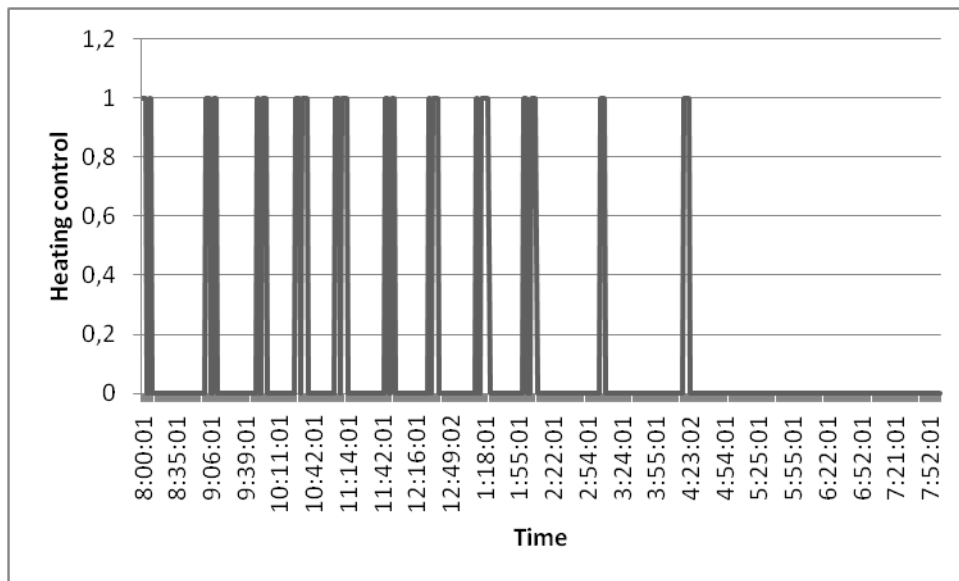


Figure 21: Heating control with model-free control

Table 7: Results evaluation for the model-free control

Output error	mean	variance
e_{T_i} for $T_i^* = 20^\circ C$	$-0.4^\circ C$	$0.6^\circ C$
e_{T_i} for $T_i^* = 16^\circ C$	$0.4^\circ C$	$0.2^\circ C$

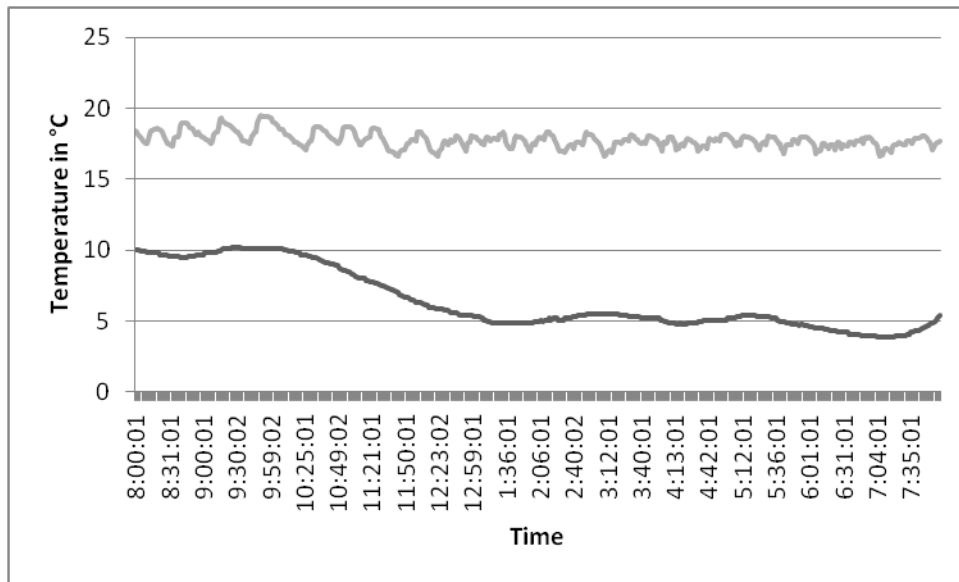


Figure 22: Temperature with model-free control (Te: Black line - Ti: Grey line)

305 8. Fault accommodation

306 An actuator fault can be described by Equation (4). An actuator fault on the
 307 heating control is simulated by a loss of efficiency equal to 50 %. Figure 22 shows
 308 results for the internal temperature with the temperature reference output equal
 309 to $18^\circ C$ during the night of 12-13 February 2014. Figure 23 demonstrates the
 310 accommodation ability of the heating control. The output temperature remains
 311 moreover very close of the internal temperature reference value.

312 Another actuator fault confirms the previous facts. Figure 24 shows the
 313 results for the internal temperature with the temperature reference output equal
 314 to $18^\circ C$ during the night of 13-14 February 2014, with a loss of efficiency equal to

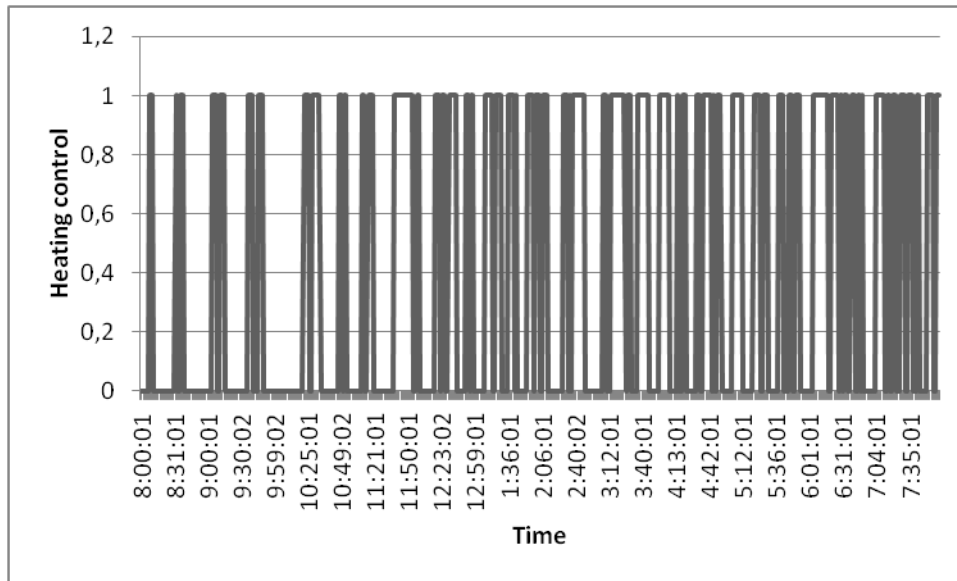


Figure 23: Heating control with model-free control

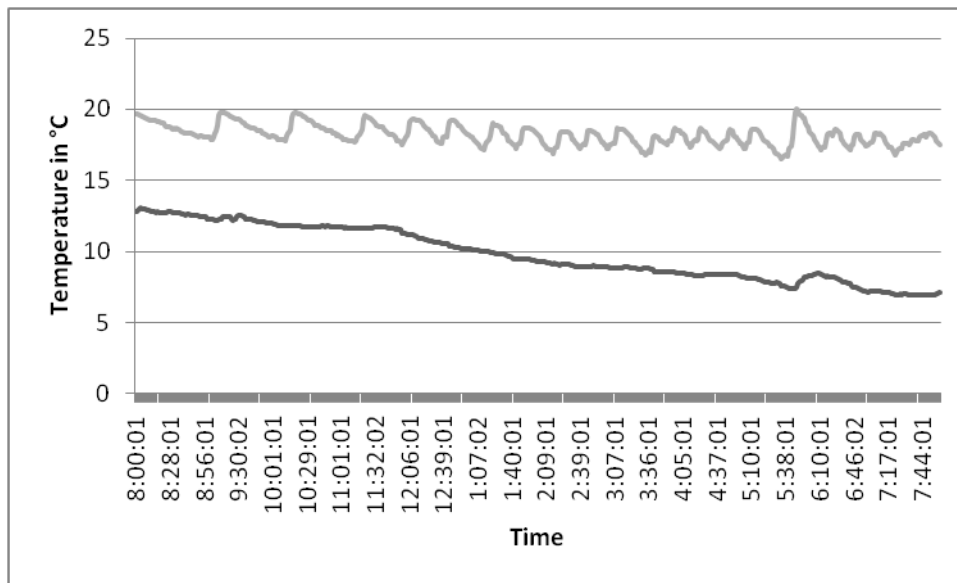


Figure 24: Temperature with model-free control (T_e : Black line - T_i : Grey line)

315 25 %. The performances displayed by Figure 25 and Table 8 are again excellent.

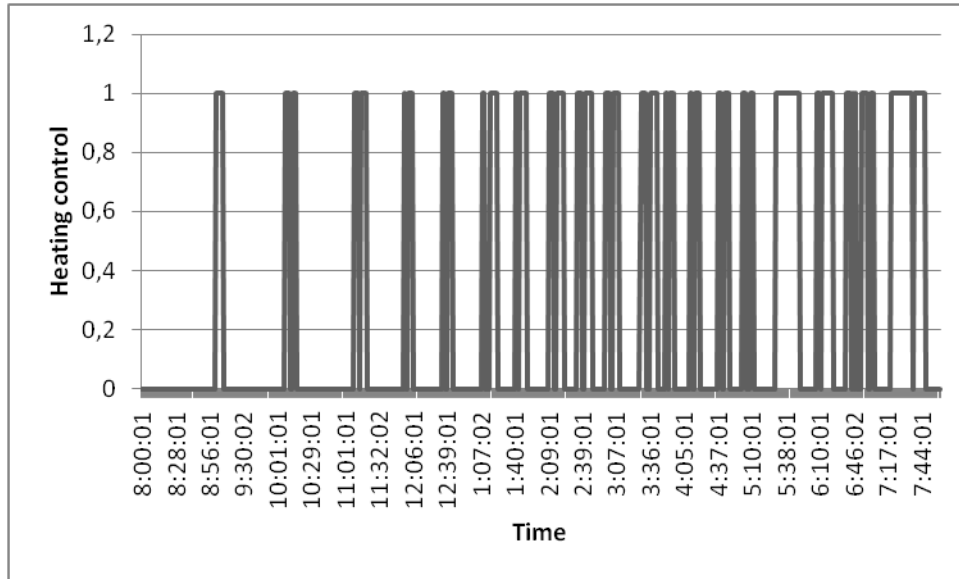


Figure 25: Heating control with model-free control

Table 8: Results evaluation for the model-free control

Output error	mean	variance
e_{T_i} with $\beta = 50\%$	$-0.2^\circ C$	$0.3^\circ C$
e_{T_i} with $\beta = 25\%$	$0.2^\circ C$	$0.5^\circ C$

316 9. Conclusion

317 Our successful model-free control strategy and its fault-tolerant capabilities
318 will be further developed by taking advantage of technologically more advanced
319 greenhouse systems. Let us mention here, among many other possibilities, a
320 regulation of the CO_2 rate. Further comparisons with various other feedback
321 synthesis techniques should also be investigated. We also hope that similar tech-
322 niques might be useful in more or less analogous domains like air-conditioning
323 in buildings (see, *e.g.*, Liu *et al.* (2013)). Data mining techniques will also be
324 considered (see, *e.g.*, Hou *et al.* (2006)).

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