



**HAL**  
open science

# Smart Autonomous Greenhouse Design Modeling and Simulation as a Variable Structure Automatic System

Nacer K M'Sirdi, Fabrice ' Aubepart, Ahmed Belhani

► **To cite this version:**

Nacer K M'Sirdi, Fabrice ' Aubepart, Ahmed Belhani. Smart Autonomous Greenhouse Design Modeling and Simulation as a Variable Structure Automatic System. IRSEC21 – 2021 9th International Renewable and Sustainable Energy, Jul 2021, Rabat, Morocco. hal-03543205

**HAL Id: hal-03543205**

**<https://hal.science/hal-03543205v1>**

Submitted on 25 Jan 2022

**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.

# Smart Autonomous Greenhouse Design

## Modeling and Simulation as a Variable Structure Automatic System

1<sup>st</sup> Nacer Kouider M'Sirdi, Fabrice Aubepart  
LiS UMR CNRS 7020, Aix Marseille University  
LiS see <http://www.lis-lab.fr>  
Marseilles, France  
nacer.msirdi@lis-lab.fr; ORCID 0000-0002-9485-6429

2<sup>nd</sup> Ahmed Belhani  
LSIACIO, University of Constantine  
Satellites, IA, Cryptographie, Internet des Objets  
Route Ain Elbey, 25000, Algeria  
ORCID 0000-0001-5595-9604

**Abstract**—This paper describes our project to design a Smart Autonomous Greenhouse (SAG) and proposes a methodology of modeling suitable for simulation, analysis and control. This kind of Systems permanently interact with its environment. The smart greenhouse is equipped with a distributed control system using IoTs, wireless-sensors and actuators. We propose a Variable Structure and Switched System Models (VSAS) class for a robust modeling and control approach. VSAS models allow us to develop a Virtual Twin of the Smart Connected Greenhouse.

**Index Terms**—Varying Structure Automatic Systems, Intelligent Control, Interaction with environment, Digital Twin of a Smart Greenhouse.

### I. INTRODUCTION

The renewable energy based systems, like a smart controlled greenhouse, operate in different environment conditions with changing climate conditions and varying characteristics. Several phenomena are involved in the process dynamic behavior like radiation, air circulation by wind, heating, humidity and temperature variations and condensation [1]–[4]. This increases the models complexity and the technology progress allows wireless local and decentralized controls to fulfill the performance requirements.

After a difficult sanitary period and several confinements, a large number of people want a home for more comfort and space. The wish for a garden with a greenhouse and a vegetable patch of 20m<sup>2</sup>.

Learning to manage an agricultural greenhouse or to maintain a vegetable garden makes it possible to overcome the restriction of movement and to combine business with pleasure by producing vegetables. The more self-contained this greenhouse, the better.

In this work, we have designed a Smart Autonomous Greenhouse (SAG) fed by renewable energies (hot water and electric energy by PVT panels), and propose an approach of modeling its dynamic behavior, for ease of stabilization of its internal state despite climate changes. This model will let us know how to deal with observability, predictability and controllability of such systems.

The process dynamic behavior is described by a VSAS model in interaction with its environment. This gives the possibility to develop a digital twin to get a Virtual Greenhouse (VSAG) to run either in parallel to show more on the internal dynamics (as virtual sensors) or can be used to predict the

behavior over the climate changes and eventual prescribed control inputs.

The Virtual SAG is useful for remote control to show the dynamic behavior. It may be used also for learning how the greenhouse behaves and can be monitored. These topics will be studied further.

Thus, we present in the section 2 the progress of our project, namely the design of a Smart Connected Autonomous Greenhouse and its simulation as a digital twin. We start by the greenhouse description and the data (measurements) acquisition and sharing process, then we proceed with the process modeling as VSAS System. The stabilization and control problem are considered in section 3, with simulations. Some stability tools useful for this approach are presented and we illustrate the effectiveness of this technique in section 4 by showing simulations results of Greenhouse model.

### II. SMART GREENHOUSE AND ITS MODEL

#### A. Process Description and Design

An SAG greenhouse can normally create optimal conditions for plant growth and manage the crop growth. It is controlled to improve the weather conditions and create optimal conditions for certain crops. It is sensitive to the external disturbances like solar radiation, temperature, wind etc. and has to filter the disadvantages like wind and rain by controlling the internal temperature, the internal hygrometry and the carbon dioxide.

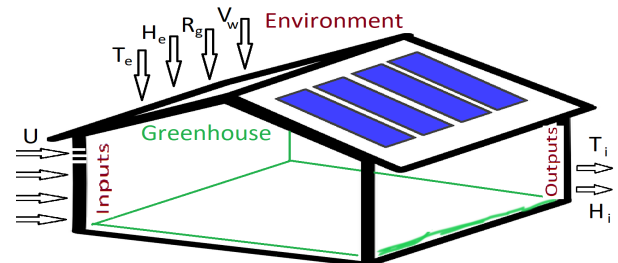


Fig. II.1. Greenhouse scheme

#### 1) Greenhouse description: : the SAG

The Smart Autonomous Greenhouse (SAG) is a simple greenhouse with glass walls and roof. The ground Surface is 19m<sup>2</sup> (3.15m large and 6.04m long with height 2.7m. The Inside Air Volume is around 45m<sup>3</sup> (see figure II-A).

There are, in a greenhouse at least, eight inputs and two outputs involved in a non linear and switched way which have to be controlled :

- 4 actuators (heating Ch, opening or ventilation Ov (%), shade Om (%) and misting system Br,
  - 4 disturbances (external temperature  $T_e$  (°C), external hygrometry  $H_e$  (%), solar radiation  $R_g$  (W/m<sup>2</sup>) and wind speed  $v_w$  (km/h)),
  - 2 controlled outputs (only) are considered here for simplicity (internal temperature  $T_i$  (°C) and internal hygrometry  $H_i$  (%)).
- This is illustrated in the Figure (II-A). Other outputs can also be considered like  $CO_2$ , crop health and water content.

The agricultural greenhouse control therefore consists of at least the 3 subsystems following:

- \* Heating: by circulation of hot water in tubes buried; the water will be heated by solar energy.
- \* The Misting: made by a ramp that runs through the greenhouse lengthwise spraying a mist of water
- \* Ventilation: made by fan and / or manual or remote controlled openings of the sashes and the roof.

The greenhouse is heated by circulation of hot water in a pipe buried in the ground. The water is heated by solar energy in PVT panels (this will be considered in further papers). Humidity is adjusted by a Misting ramp in the length of the greenhouse. A quantity of water is sprayed under fog shape. Ventilation is provided by controlled openings (on the walls and the roof). Ventilation (and windows opening) acts on temperature and humidity dynamics. Shading windows is sometimes used to reduce the effect of high solar radiation.

2) *System Variables and parameters*: Let us define the internal and external plant variables and the system parameters. The minimum number of states, input and environment variables to be measured are defined in the following table (I). Please note that several other measurement points have to be considered in the future to get the temperatures and humidity inside and outside the greenhouse. We have also to distinguish measurement ( $T_i$ ,  $T_e$ ,  $H_i$ ,  $H_e$ ) for each wall and the roof as they vary in function of orientation regard to the sun and wind direction.

In addition, we will also consider in the model the following states Variables: • the watering state of the substrate

- Water deficit
- Air Saturation humidity. • the wind speed

### 3) Measurement and Control System description: **Smart Connection**

Sensors are placed in the greenhouse to measure the internal air temperature and humidity . Other soil temperature sensors are placed near the plant rooting substrate. Outside the greenhouse we measure the external air temperature and humidity as well as the solar radiation and air flow by a wind speed sensor. A wireless network of sensors made up of connected nodes to collect the measured quantities in the greenhouse (Temperature, Humidity, radiation, wind speed etc.). We have designed the nodes (see fig (II-A3)) using a module integrating a 32-bit micro-controller, ESP32 type from the manufacturer "Espressif Systems" associated with a LORA SX1278 chip

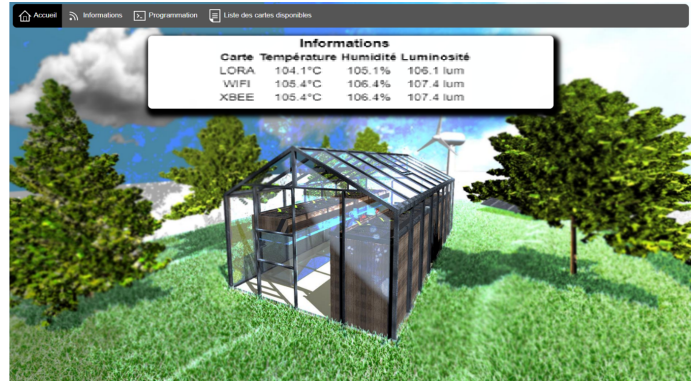


Fig. II.2. Virtual Greenhouse twin

TABLE I

SYSTEM STATE VARIABLES, STATE VARIABLES, INPUTS AND PARAMETERS		
Variable	Description	Units
$H_i$	Internal air Humidity rate	kg/m <sup>3</sup>
$T_i$	Internal air temperature	°C
$T_s$	Temperature of the soil	°C
$T_f$	Temperature of the heating fluid	°C
$T_{f,out}$	Outlet Fluid Temperature	°C
<b>Environment Variables</b>		
$H_e$	External air Humidity	kg/m <sup>3</sup>
$R_g$	Solar Radiation	
$T_e$	External air temperature	°C
$T_{f,in}$	Inlet Fluid Temperature	°C
$T_b$	Temperature of the water used for misting	°C
$v_w$	External wind velocity	m/s
$q_a$	Ventilation Air flow	g/s
$H^*$	The water content % at saturation	
<b>Input Variables</b>		
$\dot{m}_f$	Hot water flow in the heating circuit	l/s
$R_v$	Control Variable of the air flow rate	-
$F_b$	Control Variable of the Misting flow	-
$R$	Ventilation air flow Rate $R = \frac{1}{V_g} q_a$	l/s
<b>System Parameter</b>		
$S_e$	The Canopy surface exposed to sun	m <sup>2</sup>
$A_s$	Surface of the greenhouse soil	m <sup>2</sup>
$A_f$	Contact Surface of the heating circuit	m <sup>2</sup>
$A_p$	Surface of the Canopy in contact of external air	m <sup>2</sup>
$V_g$	Air Volume inside the Greenhouse	40m <sup>3</sup>
$\tau$	Absorption coefficient of the ground substract	
$K_c$	Heat Transmission Coefficient of the Roof	
a and b	Parameters of the Crop evaporation model	-

from Semtech (French inventor of LORA). This reference is well known from the LoRa practitioners.

This module is associated with an XBee communication chip thus allowing possibility of 3 wireless communication protocols modes: LORA, Zigbee and Wifi, see figure (II-A3).

The ESP32 is a series of system-on-a-chip (SoC) micro-controllers from Espressif Systems, based on Tensilica's Xtensa LX6 architecture, integrating Wi-Fi and Bluetooth management (up to LE 5.0 and 5.1).

- The proposed Network structure allows both the choices of
- the best communication mode to send the measured data (physical quantities) and
  - the type of sensors that will be associated for greater

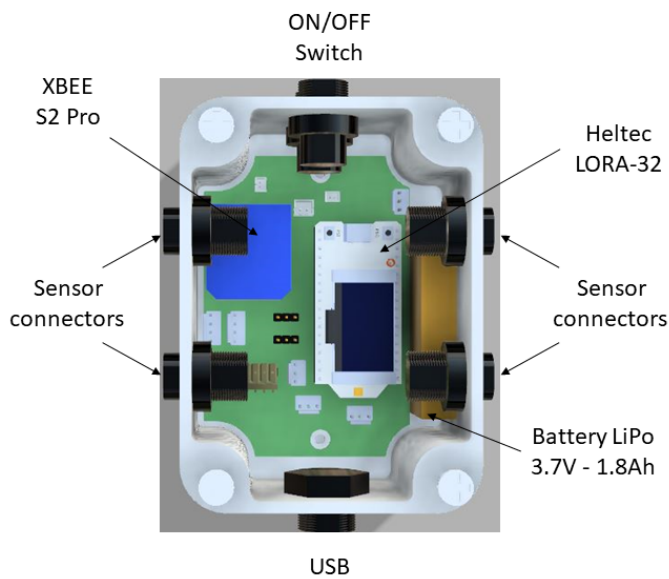


Fig. II.3. The realized Node Connection Box named 'Senscubo'

low data rate(0.3 to 100kbps);

- Zigbee : low communication distance (10 to 100 meters), middle energy consumption, data rate (20kps to 250kbps)
- In addition it allows to develop (using the process models) observers or virtual sensors to get non measured variables.

Thus, the communication protocol chosen will depend on the type of information sent and the time required between two measurements (see figure II-A3

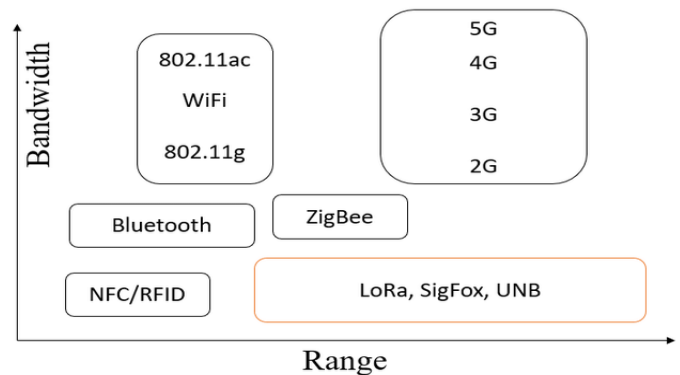


Fig. II.5. Bandwidth vs Range of wireless technology

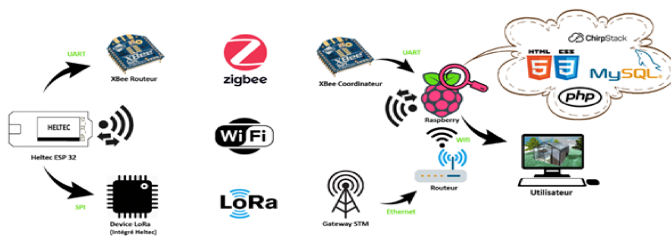


Fig. II.4. The proposed Smart Greenhouse Connection System

flexibility of use. This is made in a completely waterproof IP67 box, see figure (II-A3).

Regardless of the communication mode used, the data arrives on a mini-computer (as a Raspberry Pi) serving as a protocol and application server. This is connected to a 4G router for remote control. The Raspberry Pi also hosts a programming environment (IDE) allowing a remote user to modify or test their own programming code on any network node by selecting their MAC address. A boot-loader is used to configure the micro-controller of each node in Over-To-Air (OTA) mode via native WiFi communication. Beyond this flexibility, the choice of communication protocols (LORA, ZigBee, Wifi) for the return of the measured physical quantities is also done by programming from the Raspberry Pi.

Figure II-A2 shows an application window developed to display regularly updated measurements retrieved from a "MySQL" database integrated into the minicomputer.

This interface is particularly important to provide user-friendliness. Each of the communication protocols has its own advantages and disadvantages:

- Lora: great communication distance (2-5Km in urban areas to 15-20Km in suburban areas), low energy consumption, but

### B. VSAS Model of a Greenhouse

Let us consider a class of Multi-Input Multi-Output (MIMO) hybrid systems which interacts intermittently with their environment, in changing conditions and varying characteristics. Different phenomena, governed by discrete events, produce effects on the process behavior. This affects the system operation mode, and switches operations associated to events (like wind, rain, shadows, ...).

1) *Previous works:* : **Hybrid Systems** Some approaches are based either on a classic linear modeling using context-dependent Markov-switching [5] or on a hierarchical fuzzy logic used for commutation and supervision [6], or non linear extension of PCA [7] or driven by a prediction error generated [8], or using a bank of Kalman filters [9] or Markov chains [10].

Some authors use local black box representations and involve learning approaches such as neural networks, fuzzy logic methods or neuro-fuzzy techniques [4] [7]. These models are operating points dependent and do not allow physical interpretations.

If in identification of a such system we use a single model, then it will have to quickly adapt itself to the new environment after each change [4], [11], [12]. An appropriate control can be computed using several models combined adequately in function of the operating region.

Another way may combine local grey box representations based on partial knowledge on involved phenomena. Several local partial models are combined in a hybrid representation [6].

Some knowledge on this kind of events is necessary to follow the structure commutations and then observe, estimate

or identify the models combination and their parameters [11], [13], [14].

The models have to be adequate either for identification, behavioral analysis or for diagnosis [11]. Thus, one can consider the behavior driven by multiple models orchestrated by events governing the system operation [14], [15].

So we propose a new framework for such system for observation, identification or for diagnosis and control. To show its usefulness let us develop the model of an SAG.

2) *Variable Structure Automatic Switched Systems*: We propose a switched multi-model approach [6], [11]. Mainly several (sub) models ( $M_p$ ) are involved to represent parts of the process dynamics in different regions  $D_p \subset \mathbb{R}^n$  and time periods (for  $p = 1, 2, \dots, q$ ).

$$\dot{z}_p = f_{m_p}(z_p, u, t), \quad t \in \mathbb{R} \quad (1)$$

Each one of these partial models is valid in some state subspace  $D_p \subset \mathbb{R}^n$ .  $u$  is a set of inputs of the system.

To describe the global system, we propose then:

$$\begin{cases} \dot{z}_p(t) = f_{m_p}(z_p, x_e, u, t) & \text{for } p = 1, \dots, N_m \\ \xi_p(t_k) = F[t_{k-1}, u, x, z_p, x_e, t] & \text{for } p = 1, \dots, N_m \\ \dot{x}(t) = g_m(x, x_e, u, z_p, f_{m_p}, \xi_p, t) \end{cases} \quad (2)$$

where:

- $x(t)$  is the global system state vector (continuous),
- $x_e$  is the set of external variables or perturbations,
- $u$  are the control inputs (heat, misting, ventilation),
- $z_p$  is the state vector of the partial sub system  $M_p$ ,
- $F$  is the discrete time function defining the switching,
- $t_k$  is the time instant of the weights changes ( $\xi_p(t_k)$ ),
- $\xi_p$  the weight of the  $M_p$  models contribution to dynamics of the global system.

$g_m$  is a weighted sum of the  $P$  sub models  $f_{m_p}$  leading

$$\dot{x}(t) = \sum_{p=1}^P \xi_p(t_k) \cdot f_{m_p}(x, x_e, u, z_p, f_{m_p}, t) \quad (3)$$

These models are combined (by means of  $\xi_p(t_k)$ ), for each operating zone, by some Switching rules (see discrete events in figure 1 of [6]). In our case we do not switch between models but modify the models combination used in function of:

- **Time periods** leading to selection of some model equations, like night, day or daybreak and sunset where solar radiation is null, full or weak increasing or decreasing
- **Running logic** in the energetic behavior or command of the system, eg temperature is too low (respectively high) then start heating (respectively ventilation).
- **Interaction** and or some connection with other variables or feature like condensation on the roof or canopy due to temperature gradient.

This class of models can be referred to as a VSAS representation driven by some Discrete Event Systems.

### III. GREENHOUSE VSAS MODEL

The data collected from sensors and cameras will be used by a VR toolbox to give Greenhouse Virtual Representation model. This will allow us to watch the behavior of the greenhouse through internet.

#### A. The Greenhouse physical VSAS model

The dynamics of the greenhouse is a due to combination of physical phenomena involving transfers of energy (radiations and heat noted  $\Phi_i$ ) and of mass transfers (water and vapour fluxes noted  $Q_i$ ) taking place in the greenhouse.

The model equations can be written by deriving the appropriate energy and mass balances, for the inside temperature  $T_i$  (in °C) and humidity,  $H_i$  (in  $kg/m^3$ ) among other quantities like CO2 content.

These processes depend on the outside climate conditions, structure of the greenhouse, type and state of the crop and on the actuating control signals (typically ventilation and heating) to modify inside temperature and humidity conditions, shading and artificial light to change internal radiation, CO2 injection to influence photosynthesis and cooling by evaporation for humidity enrichment and decreasing the air temperature). In this paper, only the temperature and humidity outputs are considered.

Let  $\Phi_S$  be the heat flow and  $Q_m$  air humidity mass balance received by the greenhouse volume at time  $t$ . The temperature and the air humidity dynamics are governed by the following equations:

$$\frac{dT_i}{dt} = \frac{1}{C_p} \cdot \Phi_S(t) \quad (4)$$

$$\frac{dH_i}{dt} = Q_m \quad (5)$$

The greenhouse climate model describes the dynamic behavior of the state variables by the use of differential equations for the air temperature, humidity and CO2 concentrations. This is time dependent. In our previous work an experimental conclusion proved that are three or four periods in a day: night, day and daybreak transition, in the morning and in the evening [1], [6]. The moisture level is affected by the ventilation, the misting, the condensation of air on the walls, on the roof and the evaporation of plants and soil. This means that some equations are not always active, which means that  $\xi_p(t)$  varies during the day and depends on the controls activity.

Let  $\Phi_S$  be the heat flow balance received by the greenhouse volume at time  $t$ . It is equal to the sum of heat inflow  $\Phi_{in}$  and the heat flow produced  $\Phi_{prod}$  minus the heat losses  $\Phi_{loss}$  and consumed flow  $\Phi_{Cons}$  by the crop (assumed null).

The input heat flow is made of 4 components coming from solar radiation, ventilation, misting and heating. The flow produced is the sum of flows provided by the soil convection, plants, people in the greenhouse, etc. We will consider here only that of the ground.

$$\begin{aligned} \Phi_S(t) &= \Phi_{in} + \Phi_{prod} - \Phi_{Cons} - \Phi_{loss} \\ \Phi_{in} &= \Phi_{Ray} + \Phi_{Vent} + \Phi_{Brum} + \Phi_{Heat} \\ \Phi_{prod} &= \Phi_{Conv-Sol} + \Phi_{Plants} + \Phi_{Conv-Pers} \end{aligned} \quad (6)$$

The air humidity (vapor) mass balance is the sum of misting, evaporation, ventilation, soil evaporation, canopy condensation and roof condensation. This gives:  $Q_m = \sum_{i=1}^6 Q_{m_i}$

$$\begin{aligned} \frac{dT_i}{dt} &= \frac{1}{C_p} \cdot \Phi_S(t) \\ \frac{dH_i}{dt} &= Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \\ \frac{dT_f}{dt} &= -\frac{h_{pf} \cdot A_f}{m_f \cdot C_f} \cdot (T_f - T_s) + \frac{\dot{m}_e \cdot c}{m_f \cdot C_f} \cdot (T_f - T_{fin}) \\ \frac{dT_s}{dt} &= -\frac{h_{si} \cdot A_s}{m_s \cdot C_s} \cdot (T_s - T_i) - \frac{h_{sf} \cdot A_f}{m_s \cdot C_s} \cdot (T_s - T_{fout}) \end{aligned} \quad (7)$$

The last two equations describe the heating system where  $T_f$  is the heating fluid temperature (which enters in greenhouse with  $T_{fin}$  and leaves it with  $T_{fout}$ ) and  $T_s$  the greenhouse soil one. Let us note  $R = \frac{1}{V_g} \frac{dV_g}{dt} = \frac{1}{V_g} q_a$  the rate of air volume exchange by ventilation and  $dV_g/dt = q_a$  the air flow.

By analysis of all those thermal flows and humidity flows combination we get (see appendices for details)

$$\begin{aligned} \Phi_{loss} &= C_p \cdot h_p \cdot \frac{A_p}{V_g} \cdot (T_i - T_e) \\ \Phi_{Conv-Sol} &= h_s \cdot \frac{A_s}{V_g} \cdot (T_i - T_s) \\ \Phi_{Vent} &= -C_p \cdot \frac{dT_i}{dt} = -R \cdot C_p \cdot (T_i - T_e) \\ \Phi_{Brum} &= L_v \cdot \frac{F_b \cdot (T_i - T_e)}{V_g} \\ \Phi_{Chauf} &= m_s \cdot C_s \cdot A_f \cdot (T_s - T_f) \\ \Phi_{cons} &= 0 \end{aligned} \quad (8)$$

and for humidity balance

$$\begin{aligned} Q_1 &= R_b / 1.3 \cdot V_g \\ Q_2 &= (a + b \cdot R_g) \cdot D_i \\ Q_3 &= \frac{1}{V_g} \frac{dv}{dt} (H_i - H_e) = (H_i - H_e) \cdot R_v \\ Q_4 &= (a_s + b_s \cdot R_g) \cdot (H^* - H_i) \\ Q_5 &= C_{paroi} \cdot C_{m,h} (c_{res} \cdot H^* - H_i) \\ Q_6 &= C_{roof} \cdot C_{m,h} (H_{rouf}(T_e) - H_i) \end{aligned} \quad (9)$$

Each line of the equations (8 and 9) will be waited by the corresponding  $\xi_p(t_k) = 1$  when active or =0 when inactive. We can also consider smooth transitions from 0 to 1 and reciprocally. For example the terms function of the sun radiation may be 0 for the night, 1 for the day and 0.5 (or growing from 0 to 1) during the night-break (from 5:00 to 7:30 mornings of Summer-days) and decreasing from 1 to 0 during the daybreak (from 19:30 to 22:00).

This model representation is modular and adjustable: the weighting functions can also be adjusted depending on the region in the world.

#### IV. CONCLUSION

The VSAS approach involves the material and energy balances, then it is very well adapted to model the dynamics of a greenhouse with its structure variations. As a consequence the stability analysis and control can be easily managed. The project construction is in good progress and simulations will be presented in the conference.

The inside climate can be easily stabilized by use of control based on multiple Lyapunov functions and then observed, diagnosed and monitored.

The model is modular, this facilitate the measurements by wireless sensors with adapted sampling period for acquisition

and control trough IoTs and local feedback loops. Simulation results gave us very encouraging results and the experimental setup is in progress, this will be discussed at the conference.

Our future works will be on the observation and robust control techniques which cope with distributed electronic computing by use of IoTs and wireless technologies, as the use of a big centralized computer is avoided.

#### NOMENCLATURE

BMS	Battery Management System, page 1
ICSS	Intelligent Control of Switched Systems, page 1
SAG	Smart Autonomous Greenhouse, page 1
MIMO	Multiple Inputs Multiple Outputs, page 1
ODE	Ordinary Differential Equations, page 1
VSAS	Variable Structure Automatic System, page 1

#### ACKNOWLEDGMENT

The authors would like to thank SASV research group for this research funding.

#### REFERENCES

- [1] L. H. Rajaoarisoa, "Modélisation et analyse d'une classe de systèmes complexes à structures variables: Application à une serre agricole," Ph.D. dissertation, Aix-Marseille université soutenue en 2009, 2009.
- [2] S. Saadaoui, "Elaboration d'un modèle dynamique d'une serre agricole," Ph.D. dissertation, Rapport de stage de Master SIS / AI, LSIS, 17 Novembre 2002.
- [3] C. Monteils and M. Amouroux, "Analyse thermique de systèmes de chauffage localisé à basse température dans les serres agricoles: paillage radiant et tubes enterrés," in *J. Phys. III France 3 (1993)*, October 1993, pp. 1981–2031.
- [4] P. Salgado and J. Boaventura Cunha, "Greenhouse climate hierarchical fuzzy modelling," in *Elsvier; Control Engineering Practice 13*, 2005, p. 613–628.
- [5] R. Murray-Smith, T. Johansen, and R. Shorten, *Multiple model approaches to modeling and control*. Taylor and Francis London, 1997.
- [6] N. K. M' Sirdi, A. Rajaoarisoa, L.H. Naamane, J. Duplaix, and J. Balmat, "Switched complex system analysis for modeling, control and diagnosis," *Int Journal of Sciences and Techniques of Automatic Control*, vol. Academic Publication center 2007, hal-01966643 2007.
- [7] N. Pessel, J. Balmat, and N. M' sirdi, "Analyse discriminante pour le diagnostic: Application a une serre agricole expérimentale," in *IEEE Conference Internationale Francophone Automatique, CIFA*, vol. CIFA, Bordeaux, France, mai, june 2006.
- [8] K. Narendra, J. Balakrishnan, and M. Ciliz, "Adaptation and learning using multiple models, switching, and tuning," *IEEE Control Systems Magazine*, vol. 15, no. 3, pp. 37–51, 1995.
- [9] D. Theilliol, D. Sauter, and J. Ponsart, "A multiple model based approach for fault tolerant control in non-linear systems," *IFAC Proceedings Volumes*, vol. 36, no. 5, pp. 149–154, 2003, 5th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes 2003, Washington DC, 9-11 June 1997. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1474667017364856>
- [10] R. Murray-Smith, "Modelling human control behaviour with context-dependent markov-switching multiple models," *IFAC Proceedings Volumes*, vol. 31, no. 26, pp. 461–466, 1998, 7th IFAC Symposium on Analysis, Design and Evaluation of Man Machine Systems (MMS'98), Kyoto, Japan, 16-18 September 1998. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1474667017401364>
- [11] L. Rajaoarisoa, K. M' Sirdi, E. K. Boukas, J. F. Balmat, and J. Duplaix, "Greenhouse Climate Modeling : Observability and Identification for Supervision," in *Proceedings of the 5th International Conference on Informatics in Control, Automation and Robotics (ICINCO 08)*, Portugal, 2008. [Online]. Available: <https://hal.archives-ouvertes.fr/hal-01778919>
- [12] C. Monteils, G. Issanchou, and M. Amouroux, "Modèle énergétique de la serre agricole," in *J. Phys. IIII*, March 1991, pp. 429–454.

- [13] I. Baruch, F. Thomas, R. Garrido, and R. Gorthcheva, "A hybrid multimodel neural network for nonlinear systems identification," in *Cinvestavipn, Mexico, grant 611/1996*, 1996.
- [14] A. Belhani and N. K. M'Sirdi, "An observer based backstepping control for a greenhouse," in *2011 International Conference on Communications, Computing and Control Applications, CCCA 2011*, 2011.
- [15] N. M'sirdi, L. Rajaoarisoa, J. Duplaix, and J. Balmat, "Modelling for control and diagnosis for a class of non linear complex switched systems," in *International Conference on Integrated Modeling and Analysis in Applied Control and Automation*, 2007.
- [16] S. Lu, D. HA, E. Zamai, S. Bacha, and A. Manificat, "Simulation de performance d'un système multi-sources d'énergie en utilisant le plancher chauffant pour chauffer un bâtiment," in *International IBPSA conference*, Lyon, France, 2008.
- [17] A. van Schijndel and M. de Wit, "Advanced simulation of building system and control with simulink," in *8th International IBPSA Conference*, Eindhoven, Netherlands, 2003.
- [18] B. Bailley and R. Cotton, "Glasshouse thermal screen : influence of single and double screens on heat loss and crops environment," in *NJAE dep Note DN/G/821*, 12 1980, p. 15.
- [19] Boulard and Baille, "Analysis of thermal performance of greenhouse as a solar collector," in *Energy in agriculture*, vol. 6, 1987, pp. 17–26.

## APPENDIX A HEAT FLOW EXCHANGES

The greenhouse modeling consists of writing different thermal and water balances regulating the exchanges with the environment. Let us consider now the heat flow exchanges and the air circulation in the greenhouse.

The heat balance is equal to the sum of heat inflow  $\Phi_{in}$  and the heat flow produced  $\Phi_{prod}$  minus the heat losses  $\Phi_{loss}$  and consumed flow  $\Phi_{Cons}$ :

$$\Phi_S(t) = \Phi_{in} + \Phi_{prod} - \Phi_{Cons} - \Phi_{loss} \quad (10)$$

### a) Losses / Output heat Flow: $\Phi_{loss}$

It consists of heat losses by radiation, by convection with the ground and by conduction with the cover and the walls. The loss of greenhouse heat by radiation is low compared to the conduction of walls because the temperature differences between the different bodies having low emissivity are weak. On the other hand, it is only slowly variable, so the heat radiation flow does not appear explicitly in the greenhouse model.

Most of the losses takes place through the walls and roof of the greenhouse.  $T_e$  is the outside temperature,  $T_p$  the walls temperature,  $T_i$  the internal air temperature and  $C_p$  its thermal capacity (in J / K). The  $h_{p_e}$  and  $h_{p_i}$  are the outside and inside Heat transfer coefficient of walls (in W / m<sup>2</sup>K), respectively.

A wall, of area  $A_p$  (in m<sup>2</sup>) can be modeled by the following ordinary differential equation [16], [17]. This is essentially the convection flow with the wall which can be approximated as follows.

$$\Phi_{loss} \approx C_p \cdot h_p \cdot \frac{A_p}{V_g} \cdot (T_i - T_e) \quad (11)$$

If we denote by  $h_p$  the specific heat coefficient of the walls and we consider that the walls are simple (and not doubled), the Convection takes place through both sides of the wall, internal coefficient  $h_i$  and external coefficient  $h_e$ ; The overall coefficient then checks  $\frac{1}{h_p} = \frac{1}{h_i} + \frac{1}{h_e}$ . The coefficient  $h_p$  depends not only on the nature of the wall but also thermal agitation, so it increases with wind speed (denoted by  $v_w$ ) [18], [19],  $h_p = a + b \cdot v_w$ .

### b) Input Heat Flows : $\Phi_{in}$

The Greenhouse input flow is mainly made of 4 components coming from solar radiation, ventilation, misting and heating.

$$\Phi_{in} = \Phi_{Ray} + \Phi_{Ventilation} + \Phi_{Brumisation} + \Phi_{Heating}$$

### Solar radiation

Heat harnessed from solar radiation is transmitted by the walls and the cover of the greenhouse. This flow is correlated with the measurement of solar radiation  $R_g$ , in (kcal/m<sup>2</sup>.h), proportional to the area exposed to the sun  $A_s$  and proportional to the inverse of air volume of the greenhouse  $V_g$ ;  $K$  being the transmission coefficient of the cover, it can be expressed under the form:  $\Phi_{Ray} = \tau \cdot K \cdot R_g \frac{A_s}{V_g}$  with :

- $\tau$  : Absorption coefficient of substrat,
- $K$  : Roof transmission coefficient,
- $R_g$  : Solar radiation (global),
- $A_s$  : Ground surface (Substrat),
- $V_g$  : Greenhouse Volume

### Ventilation flow $\Phi_{Ventilation}$

Ventilation flow is  $dV_g/dt = q_a$  and we consider the air renewal rate  $R = \frac{1}{V_g} \frac{dV_g}{dt} = \frac{1}{V_g} q_a$ .

*Assumption A.1: Assumption:* We assume that the air coming from outside (with temperature  $T_e$ ) homogenizes rapidly with the air inside the greenhouse (with temperature  $T_i$ ) during a short time interval dt, ( $dV_g$ ).

Then the thermal balance of the exchanged air is:

$$\Phi_{Ventilation} = V_g \cdot C_p \cdot dT_i = -C_p \cdot (T_i - T_e) \cdot dV_g$$

Then we get the ventilation heat flow

$$\Phi_{Ventilation} = -C_p \cdot \frac{dT_i}{dt} = -R \cdot C_p \cdot (T_i - T_e)$$

*Remark A.1:* This equation is driven by  $R = \frac{1}{V_g} \frac{dV_g}{dt}$  which is a control input to adjust the ventilation flow

### Brumisation $\Phi_{Brumisation}$

*Assumption A.2:* We assume that the air with misted water (with external temperature  $T_e$ ) is immediately mixed with internal air (with temperature  $T_i$ ).

Let  $L_v$  be the latent heat of vaporization of water expressed in kcal/g and  $F_b$  the misting flow rate in g/h, the corresponding heat flow associated with misting is then:

$$\Phi_{Brumisation} = L_v \cdot \frac{F_b \cdot (T_i - T_e)}{V_g}$$

*Remark A.2:* It should be noted that  $F_b$  is linked to the temperature of the water injected in the form of a mist. The humidity rate will be controlled by  $F_b$  as well as the cooling of the indoor air in the greenhouse.

### Heating flow

The heating is provided by circulation of hot water in tubes buried in the substrate rooting. It can be expressed as a function of the temperatures of the hot water  $T_f$  and the substrate  $T_s$ . The temperature  $T_f$  varies, when going through the greenhouse, from  $T_{in}$  (at the input) to  $T_{fout}$ . This variation depends from the greenhouse soil temperature and the heating power supplied by water circulation. (for the conversion  $P$  into kcal/h = 860.P in kw).

These tubes heat a mass of earth from soil  $m_s$ , with heat capacity  $C_s$ , on an exchange surface  $A_f$ .  $m_f$  is the mass of the fluid inside the exchanger (hot water in the circuit).

$$\Phi_{Chauf} = m_s.C_s.A_f.(T_s - T_f)$$

The flow of hot water circulating in the greenhouse is  $\dot{m}_e$  and its specific heat is  $c_f$ . It brings the heat flow  $\dot{m}_e.c_f.(T_f - T_{fin})$  and during this time, its temperature evolves according to the equation:

$$m_f.C_f.\frac{dT_f}{dt} + h_{pf}.A_f.(T_f - T_s) = \dot{m}_e.c.(T_f - T_{fin}) \quad (12)$$

The heat fluxes exchanged, by the soil in addition to the quantity of heat received, are  $Q_{si}$  from the soil to the air inside the greenhouse is  $h_{si}.A_s.(T_s - T_i)$ .

$$m_s.C_s.\frac{dT_s}{dt} + h_{si}.A_s.(T_s - T_i) = -h_{sf}.A_f.(T_s - T_{fout})$$

*Remark A.3:* The greenhouse temperature control by hot water can be done either with the water temperature at the inlet  $T_{fin}$  but we will prefer to do it using the water flow  $\dot{m}_e$ . Then the substrate will transmit a heat input to the air in the greenhouse according to the temperature difference  $(T_i - T_s)$  and the ground surface-air exchange.

c) **Produced Heat flow:**  $\Phi_{prod}$

The flow produced is the sum of flows provided by the soil convection, plants, people in the greenhouse, etc. We will consider here only that of the ground.

$$\Phi_{prod} = \Phi_{Conv-Sol} + \Phi_{Plantes} + \Phi_{Conv-Personnes}$$

### The soil convection

The temperature of the soil is assumed homogeneous. The amount of heat transmitted to the ambient air of the greenhouse by convection can be written as the difference of 2 flows, one varying according to the temperature of the air inside the greenhouse ( $\phi_i = h_s.\frac{A_s}{V_g}T_i$ ) and the one of the soil, slowly varying ( $\phi_s = -h_s.\frac{A_s}{V_g}T_s$ ):

$$\Phi_{Conv-Sol} = h_s.\frac{A_s}{V_g}(T_i - T_s)$$

d) **Consumed Flow:**  $\Phi_{cons}$

The flow consumed is equal to the different flows that can be consumed in the greenhouse. For this, we can consider the life of plants. For now it is assumed to be null  $\Phi_{cons} \approx 0$ .

## APPENDIX B

### AIR FLOW EXCHANGES AND MISTING

The water content  $H_i$  of the ambient air (Humidity) of the greenhouse depends on the variations due to the Misting  $Q_1$ , to the evaporation of the plants  $Q_2$  of the ventilation  $Q_3$ , of the evaporation of the soil  $Q_4$  condensation on the walls  $Q_5$  and condensation on the roof  $Q_6$  expressed in  $g/m^2/s$ .

Condensation on the walls and the roof is negligible during the day and occurs at night.

$$\frac{dH_i}{dt} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \quad (13)$$

**The Misting  $Q_1$ :** Spraying an amount of water is done using a ramp carried by a trolley through the greenhouse. Let  $R_b$  be the flow rate of the fogger (in g/hour), which we convert in (g/kg.h) by dividing it by  $1.3V_g$  ( $1m^3$  of air weighing 1.3kg):

$$Q_1 = R_b/1.3.V_g$$

**Evaporation  $Q_2$ :**

*Assumption B.1:* We assumes the temperature of the plants equal to that of the internal air of the greenhouse ( $T_i$ ).

$R_g$  is the global external radiation, a and b are parameters to be estimated.

$D_i = H^* - H_i$  is the water deficit in the ambient air of the greenhouse. It is equal to  $H^*$  (water content at saturation) minus  $H_i$  the water content at internal temperature  $T_i$

We quantify the evaporation of plants as proportional to  $D_i$  and  $R_g$ :

$$Q_2 = (a + b.R_g).D_i$$

**Ventilation  $Q_3$ :** Ventilation is the only way the greenhouse exchanges air with its environment. It provides a volume of air  $dv$  with hygrometry  $H_e$  which replaces a volume  $dv$  with hygrometry  $H_i$ . We will therefore have the material balance:  $V_g(H_i + dH_i) = V_g(H_i) + dv.H_e - dv.H_i$  then  $V_g.dH_i = dv(H_e - H_i)$  which leads to

$$Q_3 = -\frac{dH_i}{dt} = \frac{1}{V_g} \frac{dv}{dt} (H_i - H_e) = (H_i - H_e).R_v$$

**Soil Evaporation  $Q_4$**  It takes place at the time of watering and can be neglected a time period after watering. We consider a similar equivalent model to that of plants:

$$Q_4 = (a_s + b_s.R_g).(H^* - H_i)$$

**Condensation  $Q_5$ :** The walls behave like a source of water vapor for the greenhouse, by the condensation of air (we will suppose  $c_{res} \approx 1$ )

$$Q_5 = C_{paroi}.C_{m,h}(c_{res}.H^* - H_i)$$

**Roof condensation  $Q_6$**  During the night the outside temperature is lower than the inside one. Then begins the condensation on the roof surface, which we will assume at a temperature equal to that of the air inside the greenhouse  $T_i$ .

$$Q_6 = C_{roof}.C_{m,h}(H_{rouf}(T_e) - H_i)$$