Hierarchical control of crop growth in greenhouses

Salamanca, febrero 2017
• Almería is a province located in the Southeast of Spain on the shores of the Mediterranean sea
Almería Province

• Almería has the highest hours of sunshine (annual average of 3,000 hours) and lowest rainfall in Europe

• The economy Almería
Almería Province

The largest concentration of greenhouses in the world is located in the province of Almería: 30,230 hectares
Almería Province

The largest concentration of greenhouses in the world is located in the province of Almería: 30,230 hectares
Almeria’s agriculture in numbers

- **Products**: Tomato, pepper, cucumber, watermelon, zucchini, melon, eggplant, lettuce,...

- **Production**: 3,375,970 tons with 1,803 millions € (for growers)

- **Exports**: 2,408,345 tons (75.4%), 2,194 millions € (for exporter companies)
  - UE: Germany, France, Netherland, UK
  - Non-UE: Switzerland, Russia
Almeria’s agriculture success

At the beginning, the success of Almería was the use of low-cost and low-tech greenhouses with cheap labor and able to produce off-season.
Almeria’s agriculture success

Now, there is a high competence

Countries
High tech
Excellent quality
Higher labor cost

Countries
Similar conditions
Good quality
Lower labor cost

The objectives are

How?
High Tech
CONTENTS

1. Almería’s agriculture
2. Crop growth control fundamentals
3. Greenhouse climate and fertirriation control
4. Hierarchical control approach
5. Conclusions
Crop growth control

The crop growth can be defined by biomass increment or physical dimensions of the plants

How it can be measured?

- Number and size of leaves (leaf area index, LAI)
- Dry matter (matter resulting of drying the plants)
- Fresh weight (actual weight of the plant composed by dry matter and water)
Crop growth control

A greenhouse is a closed environment in which the climate variables can be managed to achieve optimal growth.
Crop growth control

**Weather**
- Temperature
- Humidity
- Wind
- Radiation
- CO₂
- Rain

**Plagues and diseases**
- Assimilates
- Tissue
- Devastation

**Climate**
- Elements:
  - Air
  - Cover
  - Soil surface
  - Soil layers
  - Sky
- Processes:
  - Solar absorption
  - Convective
  - Conductive
  - Radiation
  - Evaporation
  - Condensation

**Crop**
- Processes:
  - Absorption
  - Transport
  - Photosynthesis
  - Respiration
  - Transpiration
  - Metabolism
  - Storage

**Greenhouse**
- Elements:
  - Na⁺
  - Mg²⁺
  - Ca²⁺
  - H₂PO₄⁻
  - NO₃⁻
  - K⁺
  - NH₄⁺
  - SO₄²⁻
  - Cl⁻
  - Fe²⁺
  - Zn²⁺
  - Mn²⁺
  - Cu²⁺

**Market**
- Prices
- Energy
- Policy

**Decision Support (controller)**
- Ventilation
- Heating
- CO₂ enrichment
- Shadow screen
- Thermal screen
- Humidification
- Irrigation
- Fertilizers

**Cultural tasks**
- Spraying
- Pruning

**Mature fruits**
- (quantity, quality)

**Residues**
- Water, ions, PPP, ...

**Fertirrigation**
Crop growth control

The greenhouse production process is composed by three interactuating systems:

Greenhouse:
- Climate
- Irrigation
- Fertilization

Crop
(hours, days)

Market
(days, week, months)

(minutes, seconds)
Crop growth control

Hierarchical control system with three layers

- Lower layer (seconds/minutes)
- Interlayer 1 (minutes/hours)
- Interlayer 2 (months)
- Upper layer (season)

Greenhouse
- Climate
- Fertirrigation
- Climate models
- Fertirrigation models
- Climate controller
- Fertirrigation controller

Crop
- Plants
- Photosynthesis Respiration Absorption Models
- Plant controller

Crop
- Growth models
- Growth controller

Market
- Market models
- Tactical controller

Real Systems Level
Model Level
Controller Level
User
Greenhouse climate control

Crop growth is governed by physiological processes related with the climate

Photosynthesis

\[
\frac{dX_{PS}}{d\tau} = c_E (V_{\text{f,\text{c}}(\tau)} - V_{\text{rm,\text{c}}(\tau)})
\]

Respiration

Modified Tomgro Model (Jones 1991, Rodríguez et al 2916)

- **leaf area index (LAI)**

\[
\frac{dX_H}{dt} = c_{\text{rm}} \cdot r(X_{T,i})
\]

\[
V_{\text{LAI}} = V_{\text{den,\text{pla}}} \left( \frac{c_{\delta}}{c_{\beta}} \right) \ln \left[ 1 + \exp \left( c_{\beta} (X_H - c_{\text{nb}}) \right) \right]
\]

- **Total dry matter**

\[
\frac{dX_W}{dt} = c_E (V_P - V_{\text{Rm}} X_W)
\]

\[
V_{\text{Rm}} = c_{\text{km}} \exp \left[ 0.0663 (X_{T,i} - 25) \right]
\]

\[
V_P = c_D \frac{c_T X_{\text{CO}_2,i} p(X_{T,i})}{c_K} \ln \left[ \frac{c_{\alpha} c_K X_{\text{rad},\text{PAR}} + (1 - m) c_T X_{\text{CO}_2,i} p(X_{T,i})}{c_{\alpha} c_K X_{\text{rad},\text{PAR}} \exp(-c_K V_{\text{LAI}} + c_T X_{\text{CO}_2,i} p(X_{T,i}))} \right]
\]
Greenhouse climate control

Control scheme

DISTURBANCES VARIABLES
- Outside air Temperature
- Outside Wind speed
- Outside Air Humidity
- Outside air $CO_2$
- Outside global radiation
- Outside Wind direction
- Rain

MANIPULATED VARIABLES (actuators)
- Ventilation
- Heating
- $CO_2$ enrichment
- Humidification
- Shade screen
- Thermal screen

CONTROLLED VARIABLES (Process)
- Temperature
- PAR radiation
- Inside air $CO_2$
- Inside air Humidity

CONTROLLERS

DISTURBANCES
The climate control problem has the following features:

- The system (greenhouse climate) is subject to strong disturbances, both measurable and nonmeasurable.
- There is a high correlation degree between several variables, like temperature and humidity, and the same actuators are used to control them.
- Greenhouse climate is a complex process that cannot be completely described by linear models (used for control purposes).
Greenhouse climate control

Designed controllers:

- PID-type control
- Gain Scheduling control
- Adaptive control
- Feedforward control
- Feedback linearization control
- Cascade control
- MPC-PWM control
- Multivariable control
- Fuzzy control
- Volterra control
- Event-based control
- Hybrid control
- …
Greenhouse climate control
Greenhouse climate control

It is possible to include other actuators in order to have more degrees of freedom;

- **CO₂ enrichment**

- Dehumidification

- **CO₂** distribution

- Heat water distribution

**DOUBLE LOOP**
Crop growth is influenced by fertirrigation variables

Water deficit

Graph showing the relationship between time (tiempo) and water deficit (g m\(^{-2}\)) for different fertirrigation variables.
Crop growth is influenced by fertirrigation variables.

**Electrical Conductivity**

![Graph showing the relationship between electrical conductivity and crop growth over time.](image)
The mechanistic model of (Thornley, 1996) has been used to model the water balance in the plants.

- PAR radiation
- CO2 concentration
- Temperature

**State variables:**
- Substrate water content
- Roots water content
- Stem water content

**Processes:**
- Transpiration
- Irrigation
- Transport by stem
- Absorption of water by the roots
Greenhouse fertirrigation control

Designed controllers based on:

- Evapotranspiration
- Solar irradiance
- Drainage
- Integrated Methods
- Moisture Content of the Soil or Substrate
- Other measurements (dendrometers, leaf temperature, etc)

Event-based GPC controller
Greenhouse fertirrigation control

Some irrigation results:

<table>
<thead>
<tr>
<th>Days</th>
<th>On/off</th>
<th>IAE [$10^3$]</th>
<th>WU [l/m²]</th>
<th>EB GPC $\beta$ = 1.5</th>
<th>IAE [$10^3$]</th>
<th>WU [l/m²]</th>
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<td>1.22</td>
<td>1.37</td>
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</tbody>
</table>
Hierarchical control approach

Hierarchical control system with three layers

- **Lower layer** (seconds/minutes): Greenhouse
  - Climate
  - Fertirrigation
  - Climate models
  - Fertirrigation models
  - Climate controller
  - Fertirrigation controller

- **Interlayer 1** (minutes/hours): Crop
  - Plants
  - Photosynthesis Respiration Absorption Models
  - Plant controller

- **Interlayer 2** (months): Crop
  - Growth models
  - Growth controller

- **Upper layer** (season): Market
  - Market models
  - Tactical controller
  - Real Systems Level
  - Model Level
  - Controller Level
  - User
Hierarchical control approach
Hierarchical control approach

- Climate
- Water
- Nutrients
- Plagues & diseases
- Agricultural practice

It is necessary to include economical criteria to obtain and sell the production when the profit will be the highest
Hierarchical control approach

Our first approach was maximize the profit

\[ J_1 = \int_{t_i}^{t_h} V_{\text{price,cr}}(\tau) X_{FF}(\tau) \, d\tau - \int_{t_i}^{t_h} V_{\cos}(\tau) \, d\tau \]

SALES INCOMES

PRODUCION COSTS

Steady state models of climate and crop growth

Function of climate variables
Hierarchical control approach

**FIRST LAYER**

*Climate control*

(time scale: minutes/seconds)

- Short term objectives
  - Setpoint management

**CONTROL INPUTS**

- Classica/Gain scheduling/
  feedback-forward control
- Greenhouse climate model

**CLIMATE CONTROL**

- Climate variables
  - Setpoint trajectories

**GREENHOUSE**

- Ventilation
- Heating
- Shade screen

**CLIMATE DISTURBANCES:**

- Leaf area index

**SECOND LAYER**

*Crop growth control*

(time scale: hours/days)

- Long term weather prediction (seasons)
- Short term weather prediction (minutes)

**CROP GROWTH CONTROL**

- Optimization algorithms and criteria
- Crop growth model

**CLIMATE OUTPUTS**

- Air temperature
- Air humidity
- PAR radiation
- (Air CO₂ concentration)

**CROP OUTPUTS**

- Dry weight
- Nodes number
- Leaf area index

**CONTROL INPUTS**

- Long term objectives
  - Type of season
  - Harvest date
  - Economic data
  - Decision rules

- Sold prices
- Energy prices
Hierarchical control approach

Trends of the trajectories

Receding Horizon Techniques

Trajectory day 1

Trajectory day 16

The profit is increased by 17%!!
Hierarchical control approach

Response under changes in the harvesting date

- Forward the date.
- Postpone the date

*Forward 10 days the 60 interval*
Hierarchical control approach

Multiobjective approach:

- Maximize profits
- Maximize quality
- Reduction of contaminants
- Maximize water efficiency
- Maximize the use of renewable energies
- Minimize energy consumption

Conflicting objectives
Hierarchical control approach

Multiobjective approach:

Maximize profit

$$J_1 = \sum_{ti}^t (pr_i \times X_{fft}) - \sum_{ti}^t (pr_g \times H_{cal} + pr_{fer} \times F_{ap} + pr_{ag} \times A_{ap})$$

$$X_{fft} = f(X_{ta}, CE)$$

$$F_{ap} = f(CE)$$

$$A_{ap} = f(X_{ta}, CE)$$

Maximize water use efficiency

$$J_2 = \frac{\sum_{ti}^t X_{fft}}{\sum_{ti}^t A_{ap}}$$

$$X_{fft} = f(X_{ta}, CE)$$

$$A_{ap} = f(X_{ta}, CE)$$

Maximize quality of tomato fruits

$$J_3 = \sum_{tf}^t (C_{SSol} + C_{av} + C_{fi}) \times 0.333$$

$$C_{fi} = f(X_{ta})$$

$$C_{SSol}, C_{av}, C_{fi} = f(CE)$$

Fresh weight of tomato fruits
Supplied fertilizers
Supplied water
Supplied energy

Fresh weight of tomato fruits
Supplied water

Brix degrees (soluble solids)
Tritrable acidity
Fruit firmness
Hierarchical control approach

Multiobjective approach:

(a) water-use efficiency (wue) - quality.
(b) profits - water-use efficiency (wue).
(c) quality-profits.
Hierarchical control approach

Multiobjective approach:
Hierarchical control approach

Multiobjective approach:

Horizon: 66 days

Profits

Quality

Water use efficiency

Non-dominated solution
Hierarchical control approach

Multiobjective approach:

Horizon: 66 days

<table>
<thead>
<tr>
<th>profits (€ m⁻²)</th>
<th>WUE (kg m⁻³)</th>
<th>quality index (%)</th>
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</thead>
<tbody>
<tr>
<td>1.113</td>
<td>26.539</td>
<td>96.062</td>
</tr>
<tr>
<td>1.752</td>
<td>36.926</td>
<td>95.963</td>
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<tr>
<td>2.606</td>
<td>50.837</td>
<td>84.563</td>
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<tr>
<td>2.657</td>
<td>44.051</td>
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</tr>
<tr>
<td>2.659</td>
<td>37.864</td>
<td>68.435</td>
</tr>
</tbody>
</table>
Hierarchical control approach

Multiobjective approach:

- Maximize the use of renewable energies
- Minimize energy consumption
Hierarchical control approach

Resource demand profile of the greenhouse
Hierarchical control approach

Resource demand profile of the greenhouse
• The control of crop growth in greenhouse is a complex system formed by subsystems with different dynamics, so a hierarchical multilayer structure is a good solution.

• The main drawback of the hierarchical architecture is to have a good model of the market behavior to predict the selling prices of production.

• The long-term and short-term weather forecast is very important, so the use of the receding horizon technique is necessary to diminish the possible errors.

• Although the main goal of crop growth control in greenhouses is to obtain the maximum profit, in a second phase it would also be useful that the high-level controller should consider other objectives which should be also converted into operational costs.

• It is necessary improve the climate and fertirrigation controllers so we purpose the use of other strategies used successful in other industrial areas.
References

Multiojective hierarchical control architecture for greenhouse crop growth

A. Ramírez-Arias*, F. Rodríguez*, J.L. Guzmán**, M. Berenguel***

Abstract

The problem of determining the strategies to control greenhouse crop growth has traditionally been tackled by using conventional optimization or applying artificial intelligence techniques. The emergence of big data has sparked new interest in research on optimization to obtain adequate climatic control strategies for the crop growth. This paper addresses the problem of greenhouse crop growth through a hierarchical control architecture governed by a high-level multiobjective optimization approach, where the solutions to this problem are found by simulating the crop and applying control strategies through multiobjective optimization techniques. The objective functions are to maximize yield, product quality, and resource efficiency, while being constrained by operational limitations and environmental factors. The architecture is designed to be scalable, and the environment variables are controlled through a hierarchical control strategy. The strategy is tested in a greenhouse environment, and the results are presented to demonstrate its effectiveness.

1. Introduction

Modern agriculture is nowadays subject to regulations in terms of quality and environmental impact, and this is a field where the application of automatic control techniques has increased in recent years (Fusaro, 2002; Klop & Koppert, 2000; Serrano, Arrieta, & González, 2001; Serrano & King, 1999). The greenhouse production system is a complex physical, chemical, and biological process. Taking place simultaneously, reacting with different responses to numerous environmental factors, and characterized by many interactions (Serrano & van Straten, 1993), which must be controlled in order to obtain the best results for the grower. Crop growth is the most significant process and is mainly influenced by surrounding environmental climatic variables (temperature, RH, solar radiation, soil moisture, and soil temperature). The strategies to control these variables are known and, in fact, the first automated systems were those that control these variables. On the other hand, the market prices fluctuate and the environment variables are hard to control, which can lead to a decrease in efficiency or reduce the final results in the soil (such as the water content). Other effects are also taken into account. Therefore, the optimal production process in a greenhouse is an aggregation of these effects, with the following objectives: an optimal crop growth (a bigger production with a higher quality), reduction of the associated costs (energy, electricity, and fertilizers), reduction of residues (less water, pesticides, and soil), and the improvement of the water efficiency. Many approaches have already been applied to this problem, but the focus is usually on individual components, and the optimal control of the greenhouse is a complex task. The greenhouse production system has been commonly developed using a hierarchical control architecture (Serrano & van Straten, 1993; Rodríguez, Berenguel, & Arzubi, 2002; Rodríguez, Guzmán, Berenguel, & Arzubi, 2009), which the
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