Optimal Control of Greenhouse Climate using Real-World Weather Data and Evolutionary Algorithms

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Overview

- Motivation
- Integrated Greenhouse Climate Model
- Optimization using Evolutionary Algorithms
- Experiments and Results
- Summary and Future Work
Motivation

Understanding the processes in the greenhouse

By development of complex models

• integrated model including
  → greenhouse climate
  → plant model (crop growth, yield)
  → outside weather conditions
  → control equipment (heating, ventilation, CO₂ injection)

• providing
  → prediction of all inside climate conditions in a 15-60 minute time interval
  → use for short time control tasks
    ⇝ optimization of crop growth / yield
    ⇝ prevention of stress
Motivation

Controlling the processes in the greenhouse

By: optimization of control
- goal: maximal yield under consideration of defined constraints

How:
- optimization of a dynamical system
- use of Evolutionary Algorithms
  - direct and simple deployment
  - incorporation of problem specific knowledge
  - incorporation of constraints
Structure of integrated greenhouse model

outside weather conditions
- air temperature
- solar radiation
- wind speed
- CO₂ concentration
- air humidity

greenhouse
- energy (temperature)
- condensation
- vapor (air humidity)

crops (sweet pepper)
- CO₂ (CO₂ concentration)

control
- heating
- ventilation
- CO₂ enrichment
- vapor injection
Simulation of the integrated model

- 4 greenhouse balance equations
  - energy balance
  - vapor balance
  - CO$_2$ balance
  - condensation / evaporation

- 2 plant balance equations
  - CO$_2$ exchange
  - transpiration

- yield / biomass (derived from CO$_2$ exchange)

- profit (yield minus control costs)

→ system of 8 first-order differential equations
  → simulated using Runge-Kutta methods of 4th(5th) order
Components of energy balance

- Solar radiation
- Air temperature outside
- Ventilation
- Change of air humidity inside
- Condensation/evaporation at cover
- Heat exchange at floor
- Heating
- Heat lost through cover
- Energy balance (temperature)
- Inside air temperature
- Outside air temperature
- Heat lost through cover
- Heat gained through cover
Components of plant model

- CO₂ exchange and transpiration are computed relative to standard conditions
- Use of parametric equations

Greenhouse model

Plant model

- CO₂ concentration inside
- Air humidity inside
- Air temperature inside
- Solar radiation
- CO₂ exchange
- Transpiration
Motivation

- calculation of a control
  - value of every control component over control time
  - methods of optimization of dynamic systems

- What do we need?
  - objective function (cost function)
  - representation of solutions / individuals
  - problem specific knowledge

- use of Evolutionary Algorithms
  - straightforward application (compared to gradient methods)
  - incorporation of problem specific knowledge
  - incorporation of constraints
Objective function (cost function)

- maximization of profit
  \[ \text{Cost} = \int_{T_S}^{T_E} \text{Profit} \, dt + \text{Penalty} \]

- prevention of stress
  \[ \text{Penalty} = \sum_{i=1}^{\text{NumConstr}} \left( W_i \cdot \int_{T_S}^{T_E} \vert (\text{Val}_i - \text{Constr}_i) \vert > 0 \right) \, dt \]

  \[ \rightarrow \text{minimal/maximal temperature} \]
  \[ \rightarrow \text{maximal CO}_2 \text{ concentration} \]
  \[ \rightarrow \text{minimal/maximal air humidity} \]
Interdependencies of profit calculation

Control
- heating
- CO₂ injection
- ventilation

Constraints
- control
- climate

Weather
- solar radiation
- temperature
- air humidity
- wind speed
- CO₂ concentration

Greenhouse climate
- temperature
- air humidity
- CO₂ concentration

Plant
- transpiration
- CO₂ exchange (biomass)

Profit
- heating
- CO₂ injection

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Incorporation of domain specific knowledge

- initialization with averaged control strategies
  - initial strategies are the result of optimization under standard (average) weather conditions
  - good control values defined for every month and for each hour
  - use multiple similar control strategies (previous / following months)

- changing domain of control variables
  - restrict domain of control variables depending on time of year
    - during winter heating is high, ventilation is low,
    - during summer ventilation is higher than during winter, ...
  - and time of day
    - during night heating is higher than during day,
    - during night ventilation is lower than during day, ...
Experiments

Weather data

- optimization for 5 consecutive days in May 1995
- weather data of Großbeeren (Berlin), 1995

Weather data used

- TEMB: floor temperature
- TEMG: cover temperature
- TEMA: air temperature outside
- FA: air humidity outside
- IGLOB: solar radiation

climate: 11.05. 0:00 – 15.05. 23:52
Experiments

Results

Greenhouse Control

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Optimization

Evolutionary Algorithms

Structure of the evolutionary algorithm

- initialization
  - creation of initial population
  - evaluation of individuals
- start
- Are termination criteria met?
  - yes
  - best individuals
- no
- generate new population
- competition
- migration
- reinsertion
- fitness assignment selection
- recombination
- mutation
- evaluation of offspring
- result

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Tools and algorithms used

**GEATbx**: Genetic and Evolutionary Algorithm Toolbox for use with MATLAB [http://www.geatbx.com/]

→ **Multi Strategy Competition EA**
  - 4 subpopulations with 50 individuals each
  - linear ranking, truncation selection, generation gap 0.9 (elitest),
  - discrete and line recombination,
  - real valued mutation (different range and precision),
  - unrestricted migration, competition between subpopulations
  → globally oriented search strategy (rough and fine search combined)

→ **Evolutionary Strategy EA**
  - 1 population with 30 individuals
  - best 5 individuals produce 6 offspring each (high selection pressure)
  - all offspring replace parents
  - no recombination
  - mutation by mutation operator of an evolution strategy (Ostermeier, Hansen, TU Berlin)
  → local search strategy (adaptation of mutation step sizes)
Summary

Advantages

• presentation of an integrated greenhouse model incl.
  → greenhouse climate
  → plant growth
  → control equipment
  → outside weather conditions

• use for short time-scale prediction tasks

• optimization using Evolutionary Algorithms

• employment of different objectives
  → profit maximization, prevention of stress, constraints

• ready for online control

• incorporation of problem specific knowledge
Summary

- comparison with different control strategies
  - constant set points for greenhouse climate
- new and enhanced plant models
  - tomato, cucumber, sweet pepper, radish
- coupling with long timescale control strategies
  - long time-scale: high level strategy,
  - short time-scale: low level strategy
- enhancements to the Evolutionary Algorithm
  - refinement of multiple strategies for subpopulations
  - multiobjective ranking of different objectives
  - employment of problem specific genetic operators

Future work
Experiments

Typical days

- optimization for April
- heating high during night (lower temperature constraint)
- ventilation around noon (upper temperature constraint 24°C)
- CO₂ injection on during day (with no or little ventilation)
Experiments

Typical days

- optimization for June
- heating on during night (lower temperature constraint)
- ventilation on during day (upper temperature constraint, 20°C better than 24°C)
- CO₂ injection on during morning (before ventilation opens)
Optimal control under changing prices

- prices of heating (energy) and CO₂ were changed
  → 3 times as high as standard price
  → 1/3 of standard price

- optimization for February

- high prices
  → biomass: 1.1 g/(m²·h)  profit: -0.09 Pf/(m²·h)
  → heating as low as possible (lower temperature constraint)
  → nearly no CO₂ injection

- low prices
  → biomass: 1.5 g/(m²·h)  profit: 0.03 Pf/(m²·h)
  → heating higher than keeping temperature above 16°C
  → during daytime CO₂ injection
Experiments

Comparisons

previously published solutions
• use of models and simulation to find better set points
  → day/night temperature
  → night CO₂ enrichment
• no immediate reaction to changing conditions (prices)

new integrated model and evolutionary algorithms
• optimal control of greenhouse climate
• applicable for different objectives
• immediate response to changing conditions
• use for online control
Representation of individuals

- individuals represent control of simulation period
  - use of 3 controls (heating, ventilation, CO₂ enrichment)
  - controls discretized at equidistant points (first order hold)
  - control step every 15 minutes
  - simulation period: 2-12 hours

\[
NumVar = \left(\frac{SimTime}{ControlStep} + 1\right) \cdot NumControl; \quad ControlStep = 0.25h; \quad NumControl = 3
\]

- divide longer optimization periods into smaller pieces
  - end states of one period are start states of next period
  - arbitrary long time periods can be calculated
  - size of optimization problem is adjustable to available computing power