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Advanced Model-Based Greenhouse Climate Control Using Multi-Objective Optimization

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Abstract

Modern greenhouse climate control requires use of advanced climate-control models; however, adoption of advanced climate-control models in today's industrial greenhouse production is hindered by the shortcoming of existing climate-control systems to support non-invasive composition of independently-developed climate-control models. Despite the fact that adoption of advanced climate-control models allows growers to optimize their production through improved energy efficiency, improved plant quality and yield as well as reduced risks for various climate-related diseases, commercial vendors of industrial greenhouse-climate-control systems have not taken action to provide the necessary support for independent extensibility in their systems so far. Present climate-control systems require the control logic of independently-developed climate-control models to be merged into a single monolithic climate-control model. Hence, addition of new climate-control models requires modification and validation of this monolithic model. In this paper, we present a new approach to extensible greenhouse climate control that allows new climate-control models to be added dynamically to the climate-control system independently of each other. There is no need for merging models into a single monolithic model, as the approach allows independently-developed models to co-exist alongside each other. The novelty of the approach is the use of a genetic algorithm to compute a balanced greenhouse climate that satisfies the multi-objective-optimization problem defined by the independently-added climate-control models. Feasibility of the approach is demonstrated through simulation of a number of selected production scenarios using a generic greenhouse simulator. The results of the simulations clearly show that the approach finds a balanced greenhouse climate that is satisfactory to the requirements of the independent climate-control models.

INTRODUCTION

In Northern Europe the production of ornamental pot plants depends on greenhouses equipped with heating and supplementary lighting systems, as heat and light are here restricting climatic factors for growth. To make this production ecologically and economically sustainable there is an urgent need for developing energy-efficient climate-control systems that do not compromise product quality and yield. However, commercially available climate-control systems cannot respond to this need, as they are based on simple monolithic climate-control models that implement rather rigid climate setpoints for heating, ventilation, screens, supplementary light etc. So even though past research projects have proposed more dynamic climate-control models that allow growers to save energy while keeping the plant development, quality and yield on a standard high level (Körner and Challa, 2003; Aaslyng et al., 1999) those models have not gained widespread adoption. Contrary to the rigid climate setpoint scheme used by commercial climate-control systems, the models proposed by past research projects use mainly photosynthesis-based heating setpoints, which are calculated based on the fact that the temperature optimum increases with ambient CO_2 level (Körner et al., 2002, 2009). With

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that, temperature is allowed to reach higher levels than with rigid temperature control, especially when taking the concept of temperature integration into account (De Koning, 1990; Körner and Challa, 2003; Sigrimis et al., 2000). A research prototype for model-based dynamic climate control was developed earlier (Rytter et al., 2009). This prototype system allows new climate-control models to be added as separate modules. However, the prototype suffers from similar problems as the monolithic model approach taken by commercial climate-control systems as each module needs to know about the other modules' effect on the greenhouse climate, in order to avoid conflicting climate setpoints. Thus, if a fast adoption pace is desired for new research results on advanced model-based greenhouse climate control, it requires the advent of extensible climate-control systems that allow new climate-control models to be added without requiring modification of existing control logic. Such extensible climate-control systems will allow researchers and industrial growers to experiment with new climate control models at a far less integration costs than is the case today.

MATERIALS AND METHODS

The approach presented in this paper has been implemented as a closed-loop control system that continuously uses feedback from the greenhouse environment to control actuators – e.g. heating systems, screens, vents, CO_2 supply and so on. The novelty of the approach is its ability to seamlessly add and remove independently-developed control logic without performing a global integrity check of the entire system. This flexibility is achieved by expressing independently-developed control logic as separate *control concerns* where each control concern 1) is a self-contained unit of functionality, 2) may be independently developed, and 3) may be safely combined with other control concerns.

One control concern could be average temperature control, i.e. temperature integration – the idea that a certain average temperature or temperature sum should be achieved every day (Körner et al., 2004). Another control concern may promote an optimum temperature for photosynthesis given the available light. The control of supplementary light may be influenced by many different control concerns – e.g. achieve certain amount of light every day, use the light when electricity prices are low, enforce user-specified "dark hours", etc. When combining independently-developed control concerns, the task of guaranteeing correct system behavior is not to ensure the absence of interaction among control concerns; it is the ability to automatically resolve conflicts. To resolve conflicts, a concern may 1) express a constraint that must always be satisfied, and 2) express a desire whose satisfaction entail the achievement of a desirable goal.

A control concern is considered to be a soft concern, when it only expresses a desire. Contrary to a hard concern that also expresses a constraint. Based on the active set of concerns, the control system must continuously choose the desired state of its actuators. Given a set of measured values, *M*, and a candidate set of actuator states, *A*, a constraint may be formulated as a boolean function *accept(M,A) → 0; 1*, where the returned value *1* designates that *A* is acceptable and *0* designates that *A* is unacceptable. *A* desire may be formulated as a function *fitness(M,A) → [0; 1]*, where *A* is more desirable as the returned value approaches *0*. The system then attempts to choose *A* so that the requirements of all control concerns are met. Specifically, all accept functions must be satisfied, and values produced by fitness functions must be minimized. The total fitness of a given actuator configuration, *A*, and a set of concerns, *C*, may be expressed using *f(A,C) → [0; 1]*, where *accept_all* is a function returning *1* if all concerns accept *A* and otherwise *0*, and *avg_fitness* is a function that calculates the average fitness of a set of concerns:

$$f(A,C) = \frac{1 - accept\_all(A,C) + avg\_fitness(A,C)}{2} \quad (1)$$

The most important objective is to satisfy all hard concerns. If this goal cannot be met, a user must be notified to arbitrate between hard concerns. With respect to soft concerns, the situation is more complicated. A soft concern that is important in one greenhouse may be less important, but still relevant, in another greenhouse. Therefore, the system allows growers to prioritize soft concerns. When comparing two possible actuator states, A_1 and A_2, the system first try to identify the better solution by only considering concerns with the highest priority – i.e. it compares $f(A_1, C_{priority\ 1})$ and $f(A_2, C_{priority\ 1})$. Only if the total fitness of the two actuator states are equally good, does the system consider concerns that are less important – i.e. first by comparing the total fitness using $C_{priority\ 2}$ and then possibly using $C_{priority\ 3}$, $C_{priority\ 4}$ and so on, until a solution is found. Given this scheme, it is guaranteed that a small improvement with respect to an important concern will always be preferred to the satisfaction of less important concerns. The problem of finding the best set of actuator states, A_{best}, is essentially a multi-objective constrained optimization problem. The system uses a genetic algorithm to find A_{best}. Prior work has shown that genetic algorithms can be successfully applied to solve multi-objective constrained optimization problems in a number of application domains (Konak et al., 2006). In particular, genetic algorithms are superior to other approaches, when the solution space produces a complex fitness landscape (Mitchell, 1998). Since the system is designed to be extensible, it must be able to combine independently-developed fitness functions, and thus a complex fitness landscape is likely to emerge. The genetic algorithm is configured so that 1) it is initialized with a population of 200 random actuator configurations, 2) selection abandons the worst 50% of each generation after having ranked each member of the population using $f(A,C)$ as explained above, 3) reproduction uses a combination of mutation and crossover to generate potential actuator configurations, and 4) the algorithm terminates either when the best solution dominates the population; that is, when the fitness of the best solution is no longer better than the mean solution, or when a predefined time period allowed for the computation has elapsed.

Note that the main contribution offered by this approach is the ability to add and remove functionality without performing a global integrity check – i.e. the achievement of improved extensibility. As explained above, this goal is achieved using a genetic algorithm to automatically resolve conflicting interests while the system is running. The detailed inner workings of the genetic algorithm and its performance characteristics are secondary topics that cannot be fully explored within the space limits of this paper.

EXPERIMENTS

This section describes the experiments undertaken to evaluate the extensibility of the presented control system. The section first describes a basic version of the control system that is capable of controlling the greenhouse climate. The system is built from hard concerns, which must always be satisfied and soft concerns that the user may prioritize. Then the section presents a version of the control system that has been extended with CO_2 and temperature control to optimize the rate of photosynthesis. These two new features were implemented as two soft concerns. Finally, the section presents an extension of the control system that uses a new screen-control concern which promotes photosynthesis.

The control system and its extensions have been implemented and tested on top of a semi-commercial greenhouse simulator that is based on simulation models using greenhouse energy fluxes and crop growth (Körner and Hansen, 2012; Körner et al., 2008). In the experiment, each version of the control system is run as add-ons to the simulator, and the results are used to validate that the system is independently extensible without compromising existing functionality.

The control system affects the greenhouse climate using five actuators: A CO_2-dosing system is activated whenever the measured CO_2 level is below a setpoint, C_{sp}; a heating system maintains a temperature in °C above a setpoint, T_{sp}; the coverage of an intermediate irradiation and isolation curtain is controlled by a setpoint, S_{sp}; and windows are used for ventilation when the actual temperature is above a setpoint, V_{sp}.

The first version of the control system is composed of 6 hard and 6 soft control concerns, each of which is interested in influencing one or more actuators. The hard concerns of the first version of the system are as follows:

- Avoid overheating prevents overheating of the greenhouse by using ventilation when appropriate – i.e. an *accept* function ensures that the ventilation temperature setpoint, V_{sp}, is chosen so that $V_{sp} < V_{max}$.
- Avoid wasteful CO_2 dosing avoids wasteful CO_2 dosing – i.e. an *accept* function ensures that C_{sp} and V_{sp} are chosen so that ventilation and CO_2 dosing do not occur simultaneously.
- Avoid wasteful heating prohibits wasteful heating of the greenhouse – i.e. an *accept* function ensures that T_{sp} and V_{sp} is chosen so that heating and ventilation is not activated simultaneously.
- CO_2 limits ensures that the CO_2 level stays within acceptable boundaries – i.e. an *accept* function enforces upper and lower limits for C_{sp}.
- Temperature limits ensures that the temperature stays within acceptable boundaries – i.e. an *accept* function imposes upper and lower limits for T_{sp}.
- Avoid excessive humidity enforces a small screen gap when greenhouse humidity is above the setpoint for relative humidity – i.e. an *accept* function ensures that S_{sp} is high (e.g. 97%) when humidity is high.

In addition to the hard concerns enumerated above, the first version of the control system also contains a number of soft concerns. The intentions of each of these soft concerns are enumerated below together with the priorities that have been used in the experiment:

- Insulation (priority 3) desires using curtains for insulation – i.e. a *fitness* function maximizes S_{sp} when the energy balance is negative; i.e. the greenhouse is losing heat to its surroundings.
- Shading (priority 3) desires using screens for shading – i.e. a *fitness* function maximizes S_{sp} when the outdoor light-intensity is high.
- Day/night CO_2 (priority 5) desires different CO_2 thresholds for day and night – i.e. a *fitness* function that minimizes the difference between C_{sp} and a day or night threshold.
- Day/night screen (priority 5) influences the curtain according to different thresholds specified for day and night – i.e. a *fitness* function minimizes the absolute difference between the S_{sp} and a day or night threshold.
- Day/night temperature (priority 5) influences the heating setpoint according to one threshold during the day and another during the night – i.e. a *fitness* function minimizes the absolute difference between the T_{sp} and a day or night threshold.
- Day/night ventilation (priority 5) influences the ventilation setpoint according to one threshold during the day and another during the night – i.e. a *fitness* function minimizes the absolute difference between the V_{sp} and a day or night threshold.

The second version of the control system is extended with CO_2 and temperature control to optimize the rate of photosynthesis (Körner et al., 2002, 2009; Aaslyng et al., 1999). It is expected that the extension will control CO_2 and temperature so that availability of more light will result in a higher photosynthesis rate. The extension adds two new soft concerns:

- Photosynthesis-optimal CO_2 (priority 3) favors a CO_2 level that promotes photosynthesis – i.e. a *fitness* function guides C_{sp} towards a value that maximizes photosynthesis.
- Photosynthesis-optimal temperature (priority 3) favors a temperature that promotes photosynthesis – i.e. a *fitness* function guides T_{sp} towards a value that maximizes photosynthesis.

The third version of the control system introduces an extension for photosynthesis-optimized screen control. It is expected that this extension will allow for utilization of more light and thus increase the photosynthesis rate even further. This extension is implemented as a single soft concern:

- Photosynthesis-optimal screen (priority 2) promotes not using screens (folded) whenever there is a potential for a higher photosynthesis rate, even though the energy balance might be negative – i.e. a *fitness* function minimizes S_{sp} when there is extra photosynthesis to be gained.

The simulation experiment consists of two system runs – once with each version. The experiments are expected to show that the control system supports the introduction of new functionality without compromising existing functionality. It is also expected that each introduced extension will improve the control system's ability to optimize the photosynthesis rate.

RESULTS AND DISCUSSION

This section presents the results of running simulations based on the extension scenarios described in the previous section. The simulation data is based on a spring day – April the 22nd – taken from a standard Danish reference year.

Figure 1 compares the results of running the first basic version of the control system and the second version of the same system that has been extended with photosynthesis-optimal temperature and CO_2 control. The figure shows setpoints and corresponding measured values for CO_2 – the topmost set of graphs – and temperature – the set of graphs below.

With respect to CO_2, it is easy to see the effect of the extension. Whereas the first version uses a fixed setpoint during the day, the second version continuously modifies the setpoint to achieve photosynthesis-optimized control. During the morning and the afternoon, the CO_2 setpoint can be lowered, and thus the extended control system can avoid dosing extra CO_2, without hampering the photosynthesis. During the middle of the day, extra CO_2 leads to improved photosynthesis.

With respect to temperature, it turns out that temperature can be lowered most of the day without hampering photosynthesis. The temperature is, however, not lowered below the minimum temperature, 15°C, that is being enforced by the temperature-limits concern. Most of the day the energy balance is positive, and thus the actual temperature is above the photosynthesis-optimized setpoint.

Compared to the photosynthesis sum gained in the first version, there is a 9% improvement by extending the system to the second version – i.e. the photosynthesis sum gained by the first version was 554 mmol/m^2 compared to 604 mmol/m^2 gained by the second version of the system.

Figure 2 compares screen control in the second version of the control system and the effect of adding photosynthesis-optimized screen control in the third version of the system. The figure shows the screen-position setpoint – the gray shaded area – and the energy balance and the photosynthesis potential given by the available natural light.

In the second version of the control system, the need for isolation unfolds the screens whenever the energy balance is negative. However, a minimum opening for humidity control is used. Whereas in the third version of the control system, the screens are unfolded earlier on in the day and kept open until later in the evening even though the energy balance during these periods is negative. This behavior is desired by the photosynthesis-optimized screen control that wants to utilize available light to generate a higher photosynthesis sum for the day.

Comparing the photosynthesis sum gained in the third version to that of the second version, there is a 12% improvement by extending the system to the third version – i.e. the photosynthesis sum gained by the third version was 677 mmol/m^2.

The two extensions described here could be introduced without any need for modifying the existing control logic. In both cases, the extended functionality did satisfy user requirements without compromising any existing functionality. Thus, the results indicate that the presented control system satisfies typical extensibility requirements in the domain of greenhouse climate control.

CONCLUSIONS

The lack of support for extensibility in industrial climate-control systems is problematic as it threatens innovation within the greenhouse sector by hindering seamless adoption of advanced climate-control models which allow growers to optimize their production through improved energy efficiency, improved plant quality and yield as well as reduced risks for various climate-related diseases. In this paper, we presented a new approach to extensible greenhouse climate control. The novelty of our approach is the ability to seamlessly add and remove the control logics of independently-developed climate-control models without performing a global integrity check of the entire control system. In our approach, the primary functional unit of control logic is expressed as control concerns. Control concerns come in two variants: Hard concerns that must always be satisfied in order to achieve acceptable system behavior, and soft concerns that constitute the desirable goals that the control system must strive for. The approach allows growers to prioritize soft concerns. This is important, because the relative importance of soft concerns often depends on the specific configuration of the greenhouse environment and the cultivar.

We have used the presented approach to implement a simple, but realistic, greenhouse control system on top of a greenhouse simulator, and demonstrated its extensibility by adding new functionality to it. First, control concerns addressing photosynthesis-optimized temperature and CO_2 control were added and then photosynthesis-optimized screen control. The results of the experiments show two things: Firstly, the control system allows both extensions to be added without compromising any existing functionality; thus, the control system is considered to be extensible. Secondly, both extensions increased the amount of photosynthesis achieved during a single day; thus, the purpose of each extension can be said to be satisfied. Based on the positive results of the two experiments, we believe that the presented approach demonstrates the ability to support the important extensibility requirements for accelerating future innovations within greenhouse climate control.

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Figures

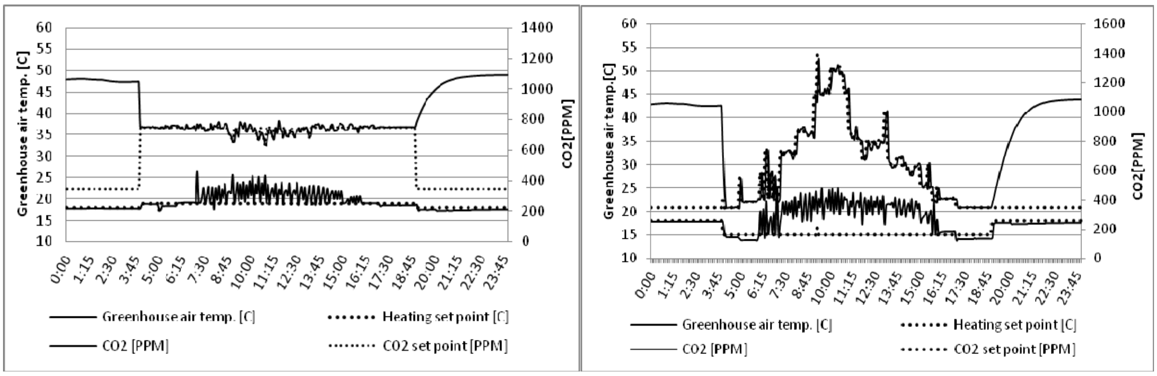

Fig. 1. The left graph shows measured and desired temperature and CO_2 in basic control scenario (first version). The right graph shows the result of extending the system with photosynthesis-optimal temperature and CO_2 control (second version).

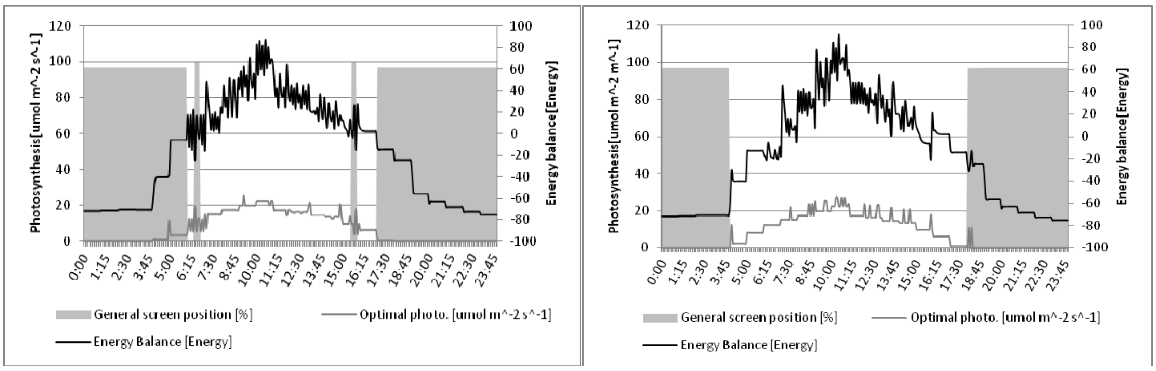

Fig. 2. The left graph shows energy balance, photosynthesis and screen position in our extended control system (second version). The right graph shows the result of adding photosynthesis-optimal screen control to the system (third version 3).