CO-SIMULATION FOR CONTROLLED ENVIRONMENT AGRICULTURE

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Motivation. *Controlled environment agriculture* (CEA) is a high-tech agricultural practice where the plant and its environment are subject to some form of control to achieve higher yields and production efficiency. CEA is critical for its impacts on food availability and costs amid the rise of severe food insecurity in Canada. CEA systems are controlled through complex key performance indicators (KPI), that experts of multiple domains, including engineers and agronomists, typically develop. The heterogeneity of such systems requires a multi-paradigm modeling and simulation approach, in which models and simulators are developed for a particular sub-problem using the most appropriate formalisms and levels of abstraction for the specific problem at hand. The separation of concerns in a multi-paradigm simulation setting is best approached through co-simulation. These technical challenges, coupled with the lack of general analytical and simulation models of biological entities, pose unique challenges in the control of CEA systems.

Challenges. There are two main challenges in the co-simulation of CEA systems: (i) *modeling biological entities* and (ii) *coupling biological entities with physics models*.
Modeling CEA systems requires representing complex entities with poorly understood or defined dynamics in their specific domains. Doing so is difficult since we cannot rely on well-defined models that capture the dynamics necessary to simulate our KPI. With co-simulation, we can model the entity's complex dynamics by composing well-defined models without being explicit about their interactions by optimizing the co-simulated system for our KPIs. Co-simulation further allows us to couple data-enabled and mechanistic models to simulate properties that prove challenging to study.
Simulating a CEA requires the coupling of not only discrete and continuous time models but also continuous models of physics with models of biology. These models often do not have well-defined interactions between their respective domains and are often causal, emergent, or non-deterministic. It is difficult to create a single monolithic biophysical model able to capture these complex dynamics. With co-simulation, we can model each component of our entities using the most appropriate formalism and delegate the development of domain-specific models to domain experts.

Methodology. We address the above challenges by developing a flexible simulation framework that couples distinct models for the entities composing our CEA. A model of the environment reproduces growing conditions, a model of a strawberry plant simulates growth and energy releases in the environment, and an energy balance model handles the exchange of energies in the air released by the environment and the plant.
The simulation of our environment is composed of two actuated physical systems: an *HVAC system* able to regulate ambient air temperature and humidity and an *artificial lighting system* emitting radiation and heat. We modeled both systems using the Discrete Event System Specification (DEVS) formalism (Chow and Zeigler 1994). Being closed under coupling, DEVS is an excellent choice to model complex systems in a bottom-up fashion, component by component.
Our plant simulator contains two co-simulated models: a *thermodynamics model* that captures the energies released by the strawberry plant in the environment and a *bio-mass allocation model* that allocates carbohydrates produced by the plant to the different organs based on daily growth conditions. We used Simulink to express both models as differential equations because of its ability to resolve algebraic loops and to more easily share our models with domain experts to receive feedback for iterative model development.
A continuous energy balance model was developed with a domain expert in thermodynamics to balance the energies output by the environment and the plant simulators. We solve the model for the new state of the environment's energy based on the previous states of the environment and the strawberry plant. We implemented this model in Simulink.

We compose our environment, plant, and energy balance models using PythonPDEVS (Van Tendeloo and Vangheluwe 2016). This composition enables us to configure the initial conditions of the growing room down to individual sensors and specific genetic coefficients proper to the plant while maintaining control over actuators. We rely on functional mock-up units (FMUs) as defined by the functional mock-up interface standard (Blochwitz et al. 2012) to co-simulate components of our system. With FMUs, we can build our system as a composition of black boxes modeled using the most appropriate formalisms and paradigms. This modular approach to development lets us build models of complex entities to represent their dynamics and enables the simulation of complex KPIs, such as the ratio between fruit yield expressed in kilograms and the energy consumed in kilowatt or the average weekly harvest yield.

Initial results. Our system can simulate both the growth of a strawberry plant and the energy consumption of the environment while considering the causal relationships of temperature and humidity exchanges between the strawberry plant and its environment.
The simulator can compute a day's worth of environmental conditions and the growth of a single strawberry plant in about 30 seconds on an ordinary laptop. We achieved appropriate performance in simulating plant growth as we can simulate a harvest cycle of 12–15 weeks in just a few hours.
Due to heavy computational requirements, we had to make concessions regarding the modeling accuracy of our environment. Our real-world CEA produces sensor measurements every two minutes, but this level of granularity is too computationally expensive and makes simulation too slow to be worthwhile. We opted to increase the interval between simulated sensor measurements from 2 to 10 minutes to reduce our computational load while maintaining a level of granularity that can still model the system's energy exchanges.

Discussion. We successfully applied our co-simulation approach to develop a simulator of a CEA for our industrial partner, capable of simulating complex KPIs like the ratio of fruit weight to energy consumption. While our methodology focused on CEA, our approach can extend to a broader cyber-biophysical context by co-simulating other biological entities with highly complex interactions and ill-defined dynamics.
Ongoing work is focusing on the calibration of simulation models to achieve more realistic simulation results. Future work will focus on integrating the developed co-simulation mechanisms into the digital twin that oversees the farm (David et al. 2023). Furthermore, we plan to enrich the set of formalisms used in our simulators to widen the scope of problems we can model and simulate.

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