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Deficit irrigation-based growth control of maize plants using hybrid model predictive / trellis decoding algorithm

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Abstract: Deficit irrigation approaches have been applied in mitigation of pressure on global freshwater availability. Data from growth of plants under different water stress conditions allows the development of growth models taking into account irrigation scheduling. In this work, a model predictive control approach combined with a modified trellis decoding algorithm is applied to control growth of maize plants under deficit irrigation conditions by specifying the irrigation schedule required to achieve specific total leaf length at the end of a specified growth period. The brute force-based algorithm allows the control of growth to within 8.5 % of the desired final total leaf length over a growth period of seven days. The designed control algorithm is an adaptable solution that can be applied to different optimization goals related to plant growth and water consumption, and allows the user to evaluate best-case and worst-case scenarios in advance, which supports decision making with regard to irrigation decisions.

Keywords: model predictive control, deficit irrigation, state machine, trellis decoding, plant growth control

1. INTRODUCTION

Global freshwater use has been increasing at an estimated annual rate of 1 %, driven primarily by agricultural demand, which currently accounts for 69 % of freshwater consumption as reported by UN-Water (2021). With a rising population, Food and Organization (2017) projects a required increase in irrigated food production of 50 % to meet global demand by 2050. Extreme weather conditions resulting from climate change present a challenge to meeting this projected demand. Coupled with the rapidly increasing abstraction of non-renewable groundwater supply reported by Rodell et al. (2018) and Wada et al. (2012), an urgent need to develop sustainable irrigation techniques that allow for increased food production to meet growing demand, while avoiding potentially catastrophic freshwater shortages can be stated.

Deficit irrigation involves supplying crops with water quantities below evapotranspiration-driven demand. The reaction of plants to reduced water availability is primarily dependent on genotypic traits that influence physiological responses to drought stress. The severity of yield reduction under deficit irrigation is additionally dependent on the growth stage, with studied determining water use efficiency values for different crops subjected to water stress at varying water stages.

A key consideration in deficit irrigation scheduling is to balance the requirement for water savings with maintaining plant available water levels high enough to prevent permanent damage, which would result in drastically reduced yields. Stresses experienced by plants under deficit irrigation are distinguished into mild and severe stress levels, based on plant ability to recover normal growth rates after removal of the stress through reirrigation.

Strategic implementation of deficit irrigation strategies has been shown to be capable of reducing water consumption by up to 39 % with a corresponding yield decline of less than 12 %, as demonstrated in Çakir (2004). In Zou et al. (2021), grain yield in maize grown under mild water stress from the late vegetative phase V8 to the end of the reproductive stage was observed to be greater than crops under full irrigation treatment, indicating that with optimal scheduling of deficit irrigation, the twin goals of minimizing water consumption and maximizing yield can both be achieved under certain environmental conditions.

2. MAIZE GROWTH MODEL DESCRIPTION

The growth rate of maize plants during the vegetative phase has been found to have a correlation with the quantity of soil available water as reported by Çakir (2004) with respect to reductions in plant height and leaf area development in plants subjected to short term water stress. Irrecoverable damage is however observed when the duration and severity of water stress is prolonged, as reported in Song et al. (2019). When appropriate deficit irrigation scheduling is applied, the growth rate and subsequent yield of plants subjected to mild water stress during the vegetative phase are observed to match fully irrigated maize plants, with the additional benefit of buffering the plant against yield losses due to water

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stress in the flowering and maturation stages as reported in Comas et al. (2019).

This work is based on an initial state-machine model of maize growth described in Söffker et al. (2019). Three primary stress levels are defined:

i) Plants whose water content is maintained above the upper stress level boundary (mild stress boundary) by daily replenishment to the maximum holding capacity of the growth substrate are described as experiencing no stress. This watering scheme is also referred to in this work as full irrigation.
ii) Plants whose water content is maintained between the upper and lower level boundaries, and whose stress duration does not exceed the chronological damage boundary are described as experiencing mild stress
iii) Plants whose water content falls below the lower level boundary, or which remain between the upper and lower level boundary for a time exceeding the chronological damage boundary are described as experiencing high stress.

The stress level at step n (SL_n) can thus be represented using the level boundaries based on gravimetric water content (in this work, though the boundaries could also be experimentally obtained for volumetric water content), LB_{MS} representing the transition point from an unstressed condition to mild stress, observable as a reversible reduction in growth rate, and LB_{HS} representing the transition point from mild stress to high stresss, observable as a irreversible reduction in growth rate, also defined as damage. An additional temporal boundary, CB_{HS} represents the maximum duration a plant can be subjected to water content levels characterised as mild stress without showing irreversible growth retardation.

Hence

$$SL_n = \begin{cases} 0, & \text{if } WC > LB_{MS} \\ 1, & \text{if } LB_{MS} \geq WC > LB_{HS} \& \; CB_{HS} = 0 \\ 2, & \text{otherwise.} \end{cases} \quad (1)$$

It has been shown in previous research that plants subjected to abiotic stresses retain a memory of the stress event for a certain duration, resulting in a catch-up phenomenon when the stress is withdrawn Lämke and Bäurle (2017). Withdrawal of the stress for an extended duration results in loss of memory. A chronological flag, CB_{Mem} is used to represent the memory retention period, becoming activated when the plant experiences stress, and deactivated when the duration of recovery after experiencing stress crosses the experimentally determined memory retention threshold. The memory of the plant can thus be represented as a binary state, with

$$M_n = \begin{cases} 1, & \text{if } (WC \leq LB_{MS} \| M_{n-1} = 1) \& \; CB_{Mem} = 1, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

When a plant is exposed to high stress, it experiences damage, which is observed as an irreversible retardation of growth rate even when the stress is later relieved by reirrigating the plant. The damage level can thus also be expressed as a binary state with

$$D_n = \begin{cases} 1, & \text{if } WC \leq LB_{HS} \| \; D_{n-1} = 1 \| \; CB_{HS} = 1, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

The concept of deficit irrigation-based growth control involves maintaining the test plants within the two states where presence of memory and absence of damage intersect, cycling the plants between periods of mild stress and subsequent recovery through reirrigation. Reducing the complexity of the initial model, in this contribution a truncated growth model is presented as illustrated in Figure 1, where dashed arrows represent no stress and continuous arrows represent mild stress. The transitions are described using a three-bit code, with the initial bit representing the presence of memory M_n, the second bit representing the current stress level SL_n (with 0 as no stress and 1 as mild stress) and the third bit representing the next state SL_{n+1}.

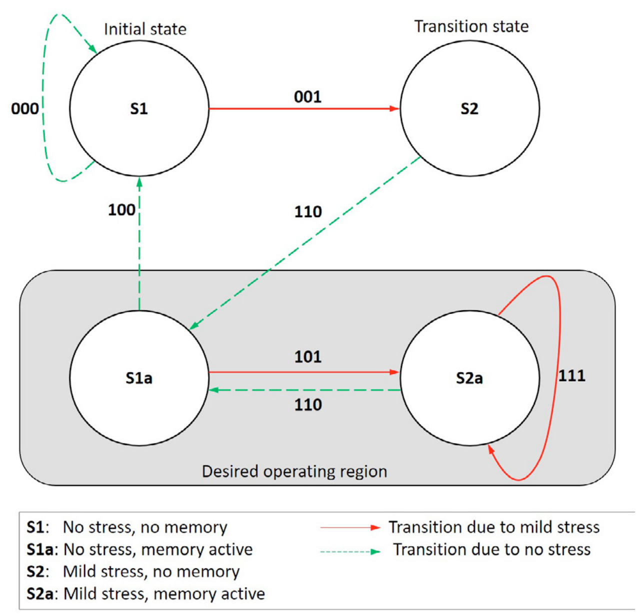

Fig. 1. Modified state machine model of maize growth with S_i denoting states of the model and arrows representing transitions

The initial progression of plant growth through the states is clearly represented in the trellis diagram shown in Figure 2. The initial state of the plants involves no stress and no memory, represented as S1. Subsequent transitions eventually evolve into a repetitive cycle, represented by the section after step k3.

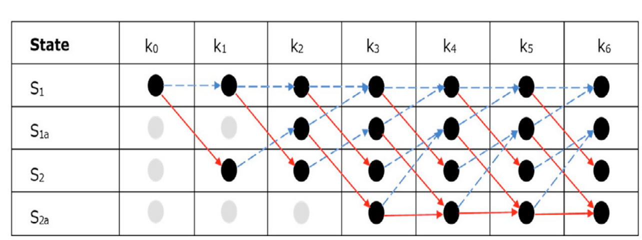

Fig. 2. Trellis diagram representation of state transitions

Linear regression is applied on historical experimental data representing each state to obtain distinct state equations to characterize the daily growth rate, expressed as total leaf elongation rate, and the evapotranspiration rate, which is represented by a function of minimum and maximum daily temperatures, minimum and maximum daily relative humidity, current total leaf length and stress state. A model predictive controller, described in the next section, is developed to achieve closed loop growth control.

3. CONTROLLER DESIGN

The control goal in this work is to achieve specific total leaf length within a fixed time period, with a secondary goal of minimizing water consumption. The state-specific elongation rate and evapotranspiration equations allow prediction of growth and water consumption given a specific watering sequence and the representative water content for fully irrigated and mild stress conditions. To achieve growth control, it is necessary to generate the closest matching irrigation sequence that would produce the required growth within the specified time. For this purpose, a hybrid algorithm combining elements of model predictive control and trellis diagram decoding was developed.

3.1 Model predictive control overview

Model predictive control, as described by Chestnut et al. (1961), utilizes a model of the controlled system to generate a control variable based on predicted future error. A set of predictions is made over a specified number of time steps, known as the prediction horizon. A set of control variables is calculated based on the predicted error over a specified number of steps, known as the control horizon. The controller applies the calculated control variable for the next time step, after which system measurements are used to update the error value. A new set of predictions and control variables, and a possibly updated system model are then generated using the updated error, a concept referred to as moving horizon.

3.2 Control algorithm design

To control growth with the proposed strategy, it is necessary to combine approaches of model predictive control with trellis decoding techniques to generate a suitable irrigation sequence. Here - based on actual measurements - the controller output is iteratively updated.

Trellis diagrams are used in telecommunications to represent coded sequences of bits that are encoded stepwise, with transitions between different states recorded in memory, and the output as a function of the current state and the input. Decoding of trellis code involves identification of the intermediate states taken to arrive at a given final output, given the initial conditions. Common decoding approaches include the Viterbi algorithm, a maximum likelihood approach described in Viterbi (1967), which produces the shortest path through a trellis diagram by examining all possible paths, and the sequential decoding algorithms, which use a sequential search for the shortest path through a trellis, with new paths only being computed as extensions of previously selected paths, and all other possible sequences systematically discarded along the way, as described by Forney (1974).

In the development of a plant growth controller, the system outputs are a sum of intermediate outputs generated from related growth and evapotranspiration equations associated with each successive state the individual goes through. Additionally, the goal of common decoding algorithms is to find the fastest path out of the trellis code, whereas the goal in this work is to find the closest matching result within a fixed duration. As a result, traditional maximum likelihood or sequential decoding approaches cannot be directly applied.

The main characteristics of each approach were considered in creating a decoding algorithm for determining the optimal path through the trellis for achieving targeted plant growth. A maximum likelihood approach provides the advantage of greater achievable accuracy, since all possible outcomes are generated before a path is selected. Multiple optimization goals can be integrated in the control decision-making, making it a more flexible approach. A sequential approach has the advantage of lower memory and processing requirements because unpursued paths are discarded at each step, allowing for longer possible prediction and control horizons.

A simplified search algorithm following the maximum likelihood approach was developed for generation of optimal irrigation sequences for achievement of the desired total leaf length. The choice was based on the relatively slow dynamics of maize growth during the vegetative stage, and constraints on the optimal length of the prediction horizon, brought about by the need to adjust the growth and evapotranspiration equations upon the appearance of new leaves. For these reasons, the advantages offered by a sequential approach are irrelevant to the application.

A description of the resultant model predictive algorithm integrating decoding of the generated trellis diagram follows.

(1) All possible irrigation sequences over a prediction horizon of duration n are generated as binary codes, with 0 representing no stress and 1 representing mild stress. The output of this step is 2^n possible combinations.
(2) Chronological constraints related to damage under prolonged mild stress and loss of memory due to an extended recovery period are applied to the search space to eliminate undesired transitions. In this work, both parameters have been set to three days based on past experimental data. The elimination process is achieved by searching the binary codes generated in the first step for consecutively occurring 0s (representing loss of memory) and consecutively occurring 1s (representing transition to damaged state).
(3) The total leaf length and cumulative water consumption for all acceptable irrigation sequences is calculated based on the state-specific leaf elongation rate and evapotranspiration equations. The calculation must be done in a stepwise manner because the functions describing elongation rate and evapotranspiration are both dependent on current total leaf length.
(4) The database is searched for the value closest to the desired total leaf length at the end of the specified time period, and the corresponding sequence selected as the output.

(5) The first bit of the generated sequence is used to calculate the required amount of irrigation to achieve the prescribed state.
(6) The next set of measurements is taken.
(7) Step (1) to (5) are repeated using the new measurements to generate a new set of predictions and control output.
(8) From the third iteration, the sum of the three most recently generated control output bits is restricted to values of 1 or 2 (to prevent loss of memory or damage due to prolonged mild stress).

An advantage of generating all possible output values is the possibility of determining the acceptable range for growth targets, with the user prompted to enter a growth target between a pre-calculated minimum and maximum. In addition, the algorithm can readily be expanded to include optimization of water consumption by comparing a specified range of closest results, and selecting based on minimum water consumption. Conversely, a search can be made with minimization of water consumption as the main goal, and the maximum achievable growth used as a secondary goal to search the resultant subset of closest matches.

4. EXPERIMENTAL SETUP

Experimental work was carried out in an indoor greenhouse housed in the Chair of Dynamics and Control at the University of Duisburg-Essen, Germany. Maize plants (Zea Mays, KWS Ronaldinio variety) were grown in 500 ml capacity PET tumblers filled with Seramis^{TM} clay granulate and positioned under artificial grow lamps which were automatically switched on and off to maintain a day length of 14 hours. Irrigation was applied once daily to levels determined by the required irrigation sequence. Fertigation was supplied using Seramis Vitalnährung für Grünpflanzen^{TM}, which provided adequate nutrition for the vegetative phase.

Four sets of five plants each were positioned in a square configuration with an infra-red camera at the center. A single maize seed was sown in each pot, and the plants were maintained under full irrigation until the third leaf tip was visible on all plants, which occured eleven days after planting. One set was designated as the control group, and received full irrigation for the entire duration of the experiment. A second group was used for validation of the stress boundaries, with the plants cycled through no stress, mild stress and high stress before being reirrigated. The remaining two groups were irrigated based on sequences generated by the developed control algorithm. The water content of the plants was monitored continously through a load cell-based measurement system on which each plant was mounted. Additional measurements taken included daily maximum and minimum temperature and relative humidity values, total leaf length and number of appeared leaves.

The stress boundaries were initially set based on expert knowledge, with plants in mild stress maintained at a water content approximately between 40 % and 70% of the holding capacity of the growth substrate. The upper stress boundary was confirmed during the course of the experiment by infrared imagery of leaf surface temperatures, which confirmed an observable deviation between the control group and the designated stress boundary validation group when the average water content in the stressed group reached a value approximately 55 % of the average water content in the control group.

5. RESULTS AND DISCUSSION

A control goal attaching equal weights to the dual goals of minimizing total water consumption and maximizing total leaf length was set for the test groups. The projected total leaf lengths were calculated based on the optimal irrigation sequences obtained from the algorithm. Measurements were taken on day 3 and day 7 of the experiments, with the irrigation sequence updated on day 4 based on obtained measurements.

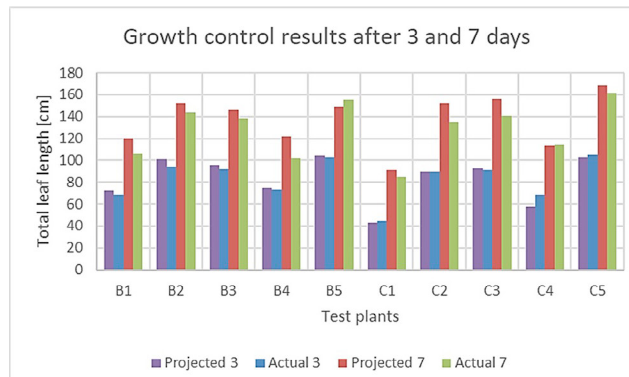

Fig. 3. Targeted growth control results

In Figure 3 resultant total leaf lengths obtained on application of the growth control algorithm after three and seven days of irrigation respectively are shown. The measured total leaf length tracks the projections closely, with a mean absolute percentage error of 4.24 % on day 3, and 8.39 % on day 7. The prediction error distribution (as a percentage of measured total leaf length) is graphically illustrated in Figure 4.

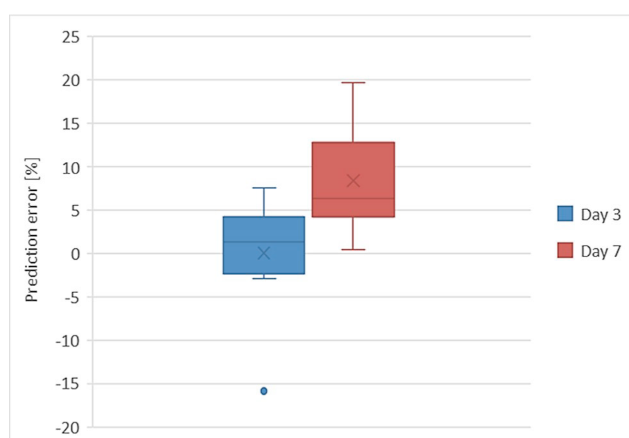

Fig. 4. Percentage error in total leaf length on days 3 and 7

The upward drift in error is attributed to the development of the plant, with the fifth leaf making an appearance on day 6 for most of the test group. To avoid distortion of the output by the unaccounted-for new leaf, the length of leaf 5 was not included in the analysis.

During the experiment, a dynamic shift of the level boundaries demarcating the region of mild stress was observed. This is possibly due to the cultivation of the maize plants in pots. As the plants develop, the threshold values for transition into stressed state trends lower, suggesting that the developing root systems of the plants are able to extract moisture from the substrate even at relatively low gravimetric water content levels. The effect of this shift in the state transition boundaries is not addressed in this work, and will be explored in future, in addition to possible shifting in the chronological memory and damage thresholds.

6. CONCLUSION

A new trellis diagram based model predictive control algorithm is presented and experimentally validated for a dual goal of maximizing growth and minimizing water consumption over a growth period of seven days. Absolute error values for the duration of the experiment are below 10 %, meeting the predefined growth control goals.

Further developments will involve automatic update of the associated growth and evapotranspiration equations upon new leaf appearance, allowing for longer durations of growth control, and extension of the algorithm to allow for variation of growth duration, allowing selection of the quickest path to the required goal in addition to the closest match after a fixed period.

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