Design of Adaptive Hybrid Machine Learning Algorithms based Model Predictive Control Schemes: Application to Precision Agriculture

CP303 - CAPSTONE PROJECT II

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Introduction

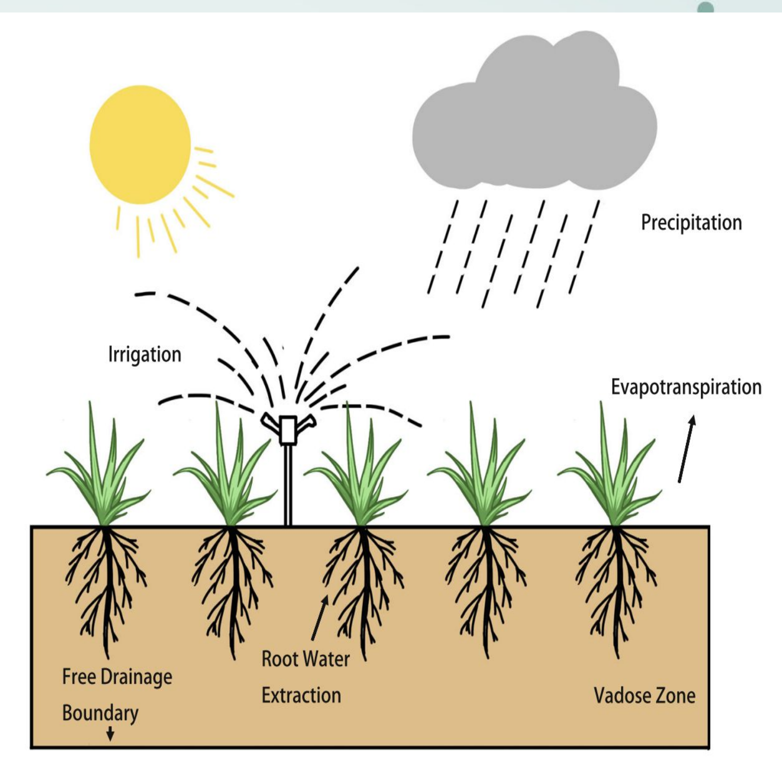
Water Scarcity: More Population & Climate Change

Farming uses about 70% of all freshwater available

Current Scenario:
Open-loop systems: Based on experience, not real-time data (low irrigation efficiency)

Precision Agriculture:

Improve irrigation efficiency
Develop smarter, data-driven watering methods
Real time feedbacks are considered



Huang et al., 2023

Model Predictive Control

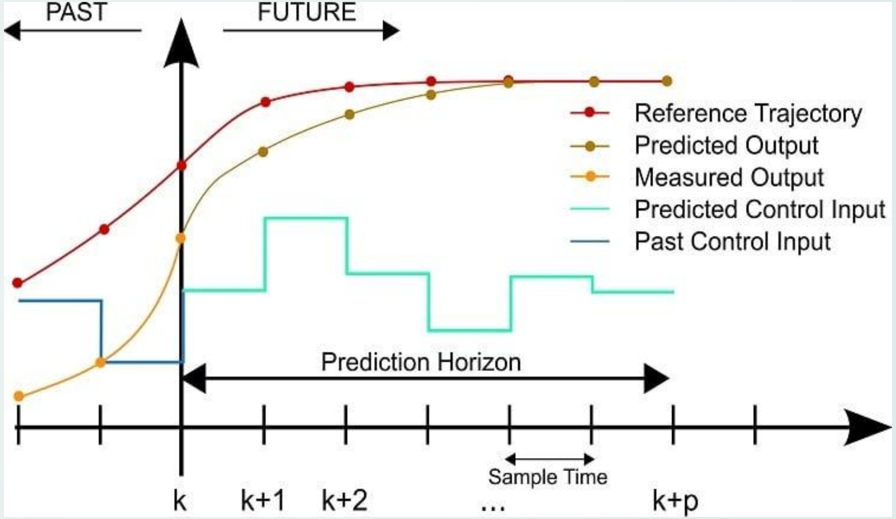
Mechanism:

- Collect real-time soil moisture data (sensors)
- Predict future soil moisture levels
- Calculate optimal irrigation actions (water)
- Apply irrigation to the field
- Repeat at next time step

Control Objective:
Minimize the amount of irrigation, while keeping the soil moisture content within target

Challenge:
High computational cost (complex soil-water dynamics)

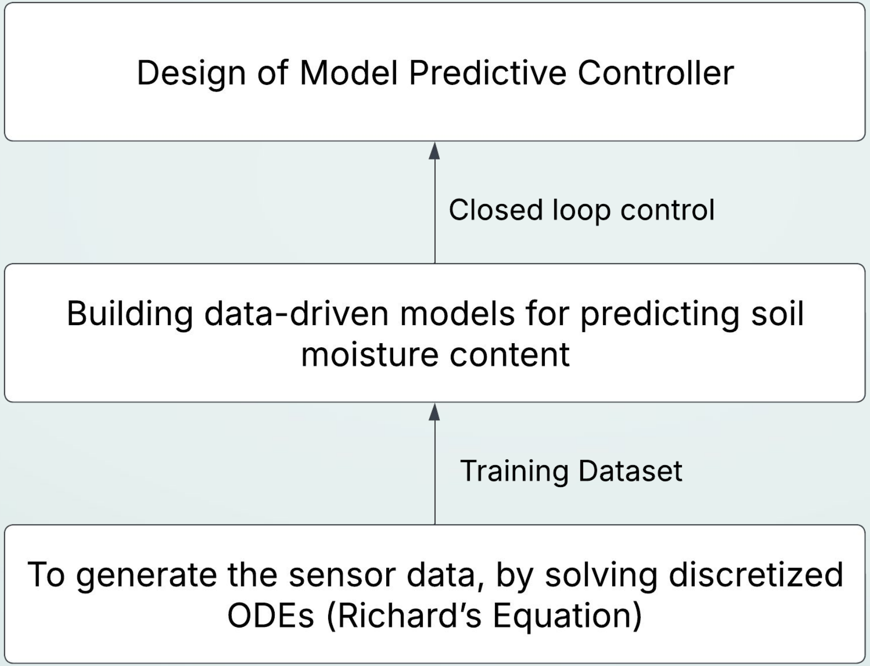
Model reduction/approx techniques: Neural Networks



https://electronics360.globalspec.com/article/17088/advantages-and-applications-of-model-predictive-control

Objective

To develop a advanced controller which can maintain the soil moisture at desired level.



Model Discretization

Soil Water Dynamics

1-dimensional **Richards equation** given by,

$$c(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - \alpha(h)\frac{K_c ET_0}{z_r},$$

van Genuchten–Mualem soil hydraulic model given by,

$$c(h) = (\theta_s - \theta_r)\alpha n\left(1-\frac{1}{n}\right)(-\alpha h)^{n-1}[1+(-\alpha h)^n]^{\frac{1}{n}-2},$$

$$K(h) = K_s\left[(1+(-\alpha h)^n)^{-\left(1-\frac{1}{n}\right)}\right]^{\frac{1}{2}}\left[1-\left[1-\left[(1+(-\alpha h)^n)^{-\left(1-\frac{1}{n}\right)}\right]^{\frac{n}{n-1}}\right]^{1-\frac{1}{n}}\right]^2,$$

Soil-water retention equation of van Genuchten

$$\theta(h) = (\theta_s - \theta_r)\left[\frac{1}{1+(-\alpha h)^n}\right]^{1-\frac{1}{n}} + \theta_r.$$

where,
h(m) - capillary potential
c (m^{-1}) - the soil capillary capacity
ET_0 (m) - reference evapotranspiration
z_r(m)- rooting depth of crop
z(m) - vertical axis of the soil
K (h) - soil hydraulic conductivity
K_c - dimensionless crop coefficient
Ks - saturated hydraulic conductivity
θs and θr - saturated and the residual soil moisture
α, n - van Genuchten–Mualem parameters(soil specific)

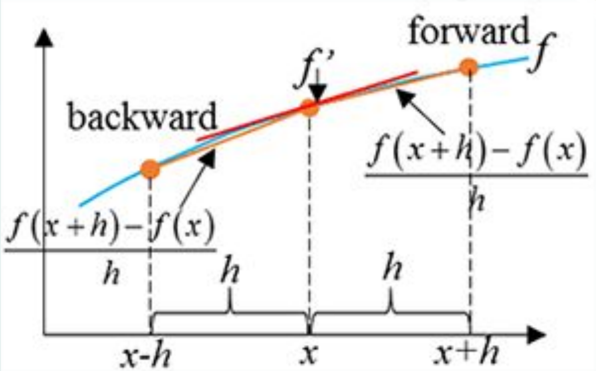
Model Discretization: Finite Difference

Assumptions:
Total depth (z) of soil is 0.5 m, evenly discretized into 26 nodes.
Center of each node is used to represent the dynamics of entire node

System Input: Irrigation/Precipitation rate
Model states: capillary potential (h) at nodes

Forward Difference:

$$\frac{\partial K(h)}{\partial z} = \frac{\partial K(h)}{\partial h} \cdot \frac{\partial h}{\partial z} \Longrightarrow \frac{\partial K(h)}{\partial z} = \frac{\partial K(h)}{\partial h} \cdot \frac{h(z+\Delta z) - h(z)}{\Delta z}$$



https://www.multiphysics.us/FDM.html

Boundary Conditions:

Top: $$\left.\frac{\partial h(t)}{\partial z}\right|_T = -1 - \frac{I(t)+P(t)}{K(h(t))},$$

Bottom: $$\left.\frac{\partial h(t)}{\partial z}\right|_B = 0,$$

Model Discretization Continued..

After Model Discretization (PDE to ODEs),
[time domain]

$$\frac{dh_n}{dt} = f(h_{n-1}, h_n, h_{n+1})$$

Generalized form of ODEs, (n = 1, 2, 3, ………., 23, 24)

$$\frac{dh_n}{dt} = \left(\frac{K(h_n)}{C(h_n)\cdot\Delta z}\right)\cdot\left(\frac{h_{n+1}-2h_n+h_{n-1}}{\Delta z}\right) + \left(\frac{1}{C(h_n)}\right)\cdot\frac{\partial K}{\partial h}\cdot\left(\frac{h_{n+1}-h_n}{\Delta z}\right)\cdot\left(\frac{h_{n+1}-h_n}{\Delta z}+1\right) - \frac{C_0}{C(h_n)}$$

Non-linear differential term

Relations from BCs,

$$h(1) = \Delta z\left(1+\frac{I_{\text{val}}+P_t}{K(h(1))}\right) + h(2)$$

non-linear

$$h(25) = h(26)$$

Open Loop Simulation: MATLAB

1. Non-linear solver: **fsolve**

```
fsolve('algebraic_equation' ,H1_initial);
```

2. Ordinary Differential Equations solver**: ode45**
(variable step solver to approximate the solution of an ODE)

```
[t, H_vals] = ode45(@(t, H) pde_model(H), time_span, H_initial);
```

41 X 24 → h_2, h_3, h_4, …………, h_{24}, h_{25}

↓

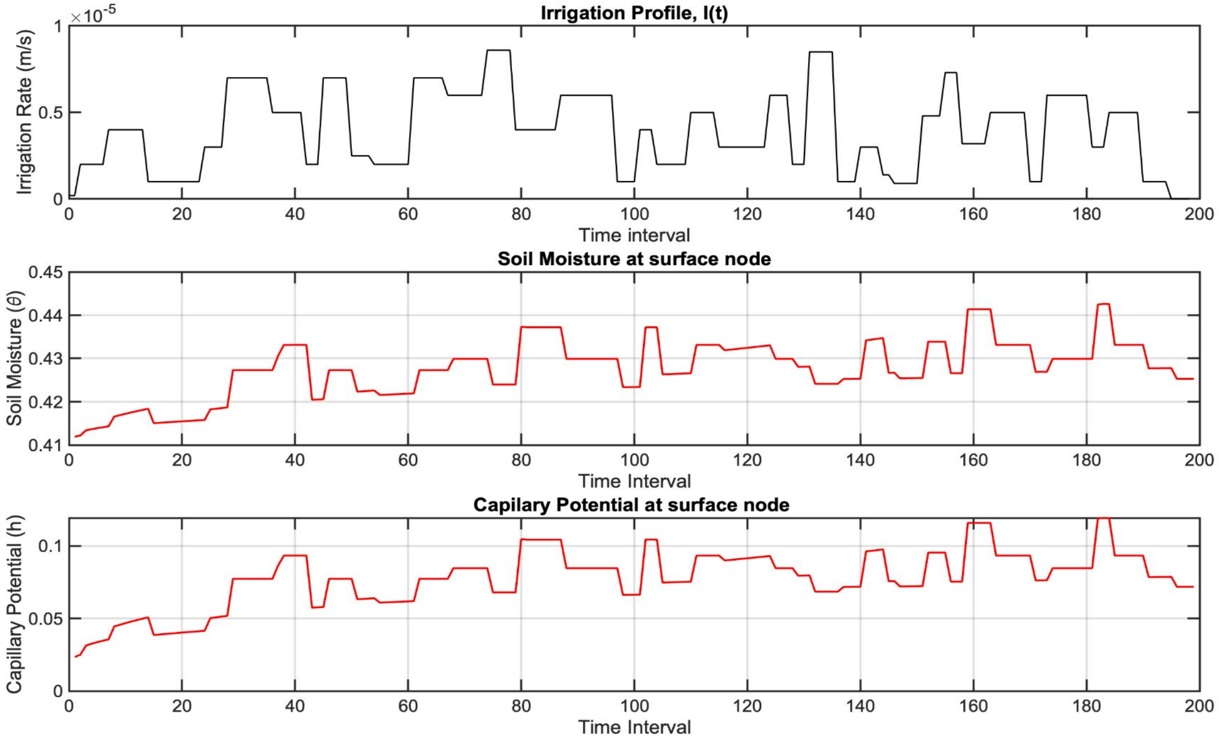
Calculate h_1 and h_{26} using the boundary conditions

↓

Calculate the soil moisture profile for all 26 nodes

3. Non-linear differential term: Numerical Jacobian

Results



Irrigation Profile, I(t)
$\times 10^{-5}$
Irrigation Rate (m/s)
1
0.5
0
0 20 40 60 80 100 120 140 160 180 200
Time interval
Soil Moisture at surface node
Soil Moisture (θ)
0.45
0.44
0.43
0.42
0.41
0 20 40 60 80 100 120 140 160 180 200
Time Interval
Capilary Potential at surface node
Capillary Potential (h)
0.1
0.05
0
0 20 40 60 80 100 120 140 160 180 200
Time Interval

Conclusion & Future Work

In summary, this work focused on:

- Discretizing Richard’s equation (PDE) in the z-direction using the finite difference method.
- Obtaining and solving the system of 24 ODEs in MATLAB with boundary conditions.
- Deriving capillary potential (h) and soil moisture profile (θ) at nodes.
- Generating sensor data (training set) for model development.

Future work:

- To develop deep learning based predictive model which can predict the soil moisture content for longer periods of time.

- To integrate the developed model with the advanced control scheme to maintain the soil moisture at desired operating zones.

References

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THANK YOU