Preparation of Papers for IEEE Trans on Industrial Electronics (Apr. 2021)

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***Abstract*—These instructions give you guidelines for preparing papers for IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS. Use this document as a template. The electronic file of your paper will be formatted further at IEEE. Paper titles should be written in uppercase and lowercase letters, not all uppercase. Avoid writing long formulas with subscripts in the title; short formulas that identify the elements are fine (e.g., "Nd-Fe-B"). Do not write "(Invited)" in the title. Write full names of authors in the author field. Define all symbols used in the abstract. Do not cite references in the abstract. Do not delete the blank line immediately above the abstract; it sets the footnote at the bottom of this column.**

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I. System Identification

A. ARX Model

We have chosen to represent the system in *discrete time*,

$$y_t + a_1 y_{t-1} + \cdots + a_n y_{t-p} = b_1 u_{t-1} + \cdots + b_q u_{t-q} \quad (1)$$

$$\theta = \left[a_1, \ldots, a_p, b_1, \ldots, b_q\right]^T \quad (2)$$

$$\varphi(t) = \left[-y_{t-1} \cdots - y_{t-p}, u_{t-1} \cdots u_{t-q}\right]^T \quad (3)$$

$$y_t = \varphi_t^T \theta_t \quad \forall t \in (1, N) \quad (4)$$

For a given system we can collect inputs and outputs over a time interval t

$$Z^N = \left\{u(t_0), y(t_0), \cdots, u(N), y(n)\right\} \quad (5)$$

$$\hat{\theta} = \arg\min_x V_N(\theta) + \lambda(\theta - \theta^*) R(\theta - \theta^*) \quad (6)$$

The ARX(p, q) model is given by:

$$y_t = \sum_{i=1}^{p} \varphi_i y_{t-i} + \sum_{j=1}^{q} \beta_j x_{t-j} + \epsilon_t \quad (7)$$

B. Piecewise Linear function

Algorithm 1 Grouping Time Series Data by Bin Medians

Require: Time series data $y = \{y_1, y_2, \ldots, y_T\}$, excitation data $u = \{u_1, u_2, \ldots, u_T\}$, bin size n
Ensure: Grouped data by bin medians
Divide the time series y into bins of size n
for $i = 1$ to $\lceil \frac{T}{n} \rceil$ **do**
    $B_i \leftarrow \{y_{(i-1)n+1}, y_{(i-1)n+2}, \ldots, y_{\min(in,T)}\}$
    Compute the median m_i of the bin B_i
end for
Group the data in y by their corresponding bin medians m_i

II. Inflow Estimation

The considered wastewater pumping station, only the outflow and the height are measured, while the inflow is not measured or estimated. Therefore, in order to estimate the inflow of the tank, we implemented an observer by using the tank equation where the instantaneous rate of change of the height dh is proportional to the difference between the inflow and the outflow of the tank, scaled by the area of the tank, as pointed Eq.8.

$$h_t = h_0 + \frac{T_s}{A}(Q_{in,t} - Q_{out,t}) + v_t \quad (8)$$

where A, the cross-sectional area of the tank, T_s is the sampling time of the measurements, $Q_{in,t}$ and $Q_{out,t}$ are the measured inflow and outflow respectively, and v_t is the measurement noise.

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By defining the the inflow $Q_{in,t}$ any time t, the hidden state the Eq.8, w_t the process noise, Q is the covariance of the process noise, and R is the measurement noise covariance.

$$Q_{in,t+1} = Q_{in,t} + w_t$$

The states can be estimated by means of the Kalman filter, at any given time t

Prediction Step:

$$\hat{Q}_{in,t+1|t} = \hat{Q}_{in,t|t}$$
$$P_{t+1|t} = P_{t|t} + Q$$

where Q is the covariance of the process noise.

Update Step: Compute the Kalman Gain and update the estimate with the measurement:

$$\Delta h_{t+1} = h_{t+1} - z_{h,t+1}$$
$$\Delta Q_{t+1} = \hat{Q}_{in,t+1|t} - z_{Q_{out},t+1}$$
$$\hat{Q}_{in,t+1|t+1} = \hat{Q}_{in,t+1|t} + K_{t+1}\left(\frac{A}{T_s}\Delta h_{t+1} - \Delta Q_{t+1}\right)$$

III. Inflow Forecast

IV. Hierarchical Model Predictive Control

A. Higher-Level MPC

$$\min_{\zeta,} \sum_{t=1}^{T} \Gamma \|E\|_t^2 + \Lambda_t^T \sigma_t \tag{9a}$$
$$\text{s.t.} \quad \forall \sigma_t \geq 0 \tag{9b}$$
$$\zeta_t = \sum_{j=1}^{3} \zeta_{t-1} \tag{9c}$$
$$Q_{in,t} \leq 0 \tag{9d}$$
$$h_{min} \leq h_t \leq h_{max} \tag{9e}$$
$$E_{min} \leq E_t \leq E_{max} \tag{9f}$$

B. Lower-Level MPC

$$\min_{\omega,E,P,Q_{\text{out}}} \sum_{k=1}^{h} \mathcal{Q}\|h_k - h_r\|^2 + \mathcal{R}\|\omega_k\|^2 + \Gamma\|E\|_k^2 + \Lambda_k^T \sigma_k \tag{10a}$$
$$\text{s.t.} \quad \forall \sigma_k \geq 0,\ l \geq 0 \tag{10b}$$
$$Q_{\text{out},k} = \sum_{j=1}^{3} Q_{out_{j,k-1}} \tag{10c}$$
$$E_k = \sum_{j=1}^{3} E_{k-l} \tag{10d}$$
$$P_k = \sum_{j=1}^{3} P_{k-l} \tag{10e}$$
$$Q_{in,k} = \tilde{Q}_{in,k-1} \tag{10f}$$
$$h_k = \frac{1}{A}\left(\tilde{Q}_{in,k} - Q_{out,k}\right) \tag{10g}$$
$$\omega_l - \sigma_\omega \leq \omega_k \leq \omega_u + \sigma_\omega \tag{10h}$$
$$P_l - \sigma_P \leq P_k \leq P_u + \sigma_P \tag{10i}$$
$$h_r - \sigma_{h_r} \leq h_k \leq h_l + \sigma_{h_r} \tag{10j}$$

C. References

This is the paper I am citing [1]

References

[1] A. Quattrociocchi, R. K. Subroto, W. M. Oppedijk, and T. Dragičević, "Energy efficiency optimization of a wastewater pumping station through iot and ai: A real-world application of digital twins," in *IECON 2023-49th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1–6. IEEE, 2023.