Ke LIU, Mufeng WANG, Rongkuan MA, Zhenyong ZHANG, Qiang WEI, 2022. Detection and localization of cyber attacks on water treatment systems: an entropy-based approach. *Frontiers of Information Technology & Electronic Engineering*, 23(4):587-603. https://doi.org/10.1631/FITEE.2000546

Detection and localization of cyber attacks on water treatment systems: an entropy-based approach

Key words: Industrial cyber-physical system; Water treatment system; Intrusion detection; Abnormal state; Detection and localization; Information theory

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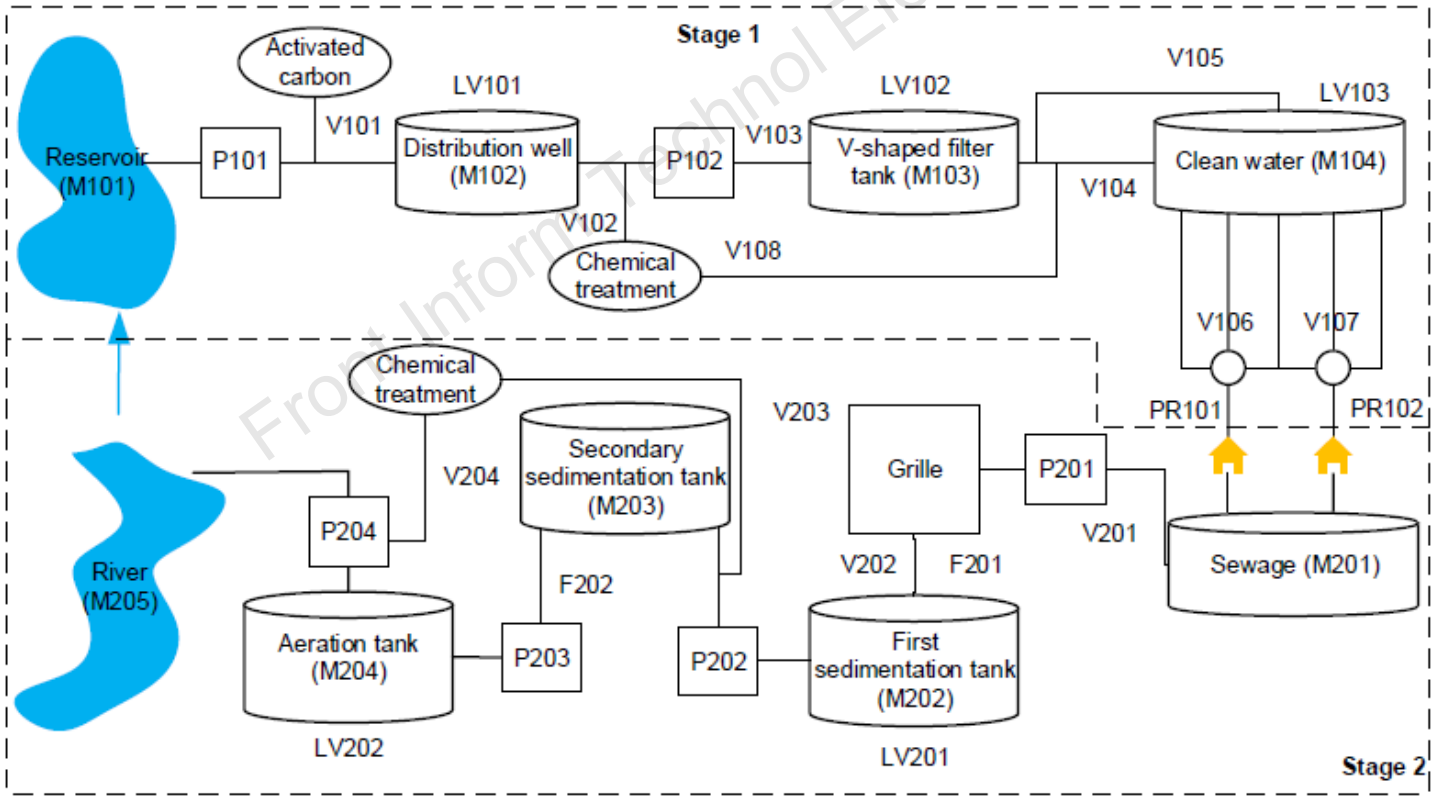
Motivation

- In water treatment systems (WTSs), few types of metadata are used, which limits the performance of the intrusion detection system (IDS).
- Most existing IDSs are used to locate intrusion points rather than abnormal points. However, abnormal point localization is more helpful in recovering the system than intrusion point localization.

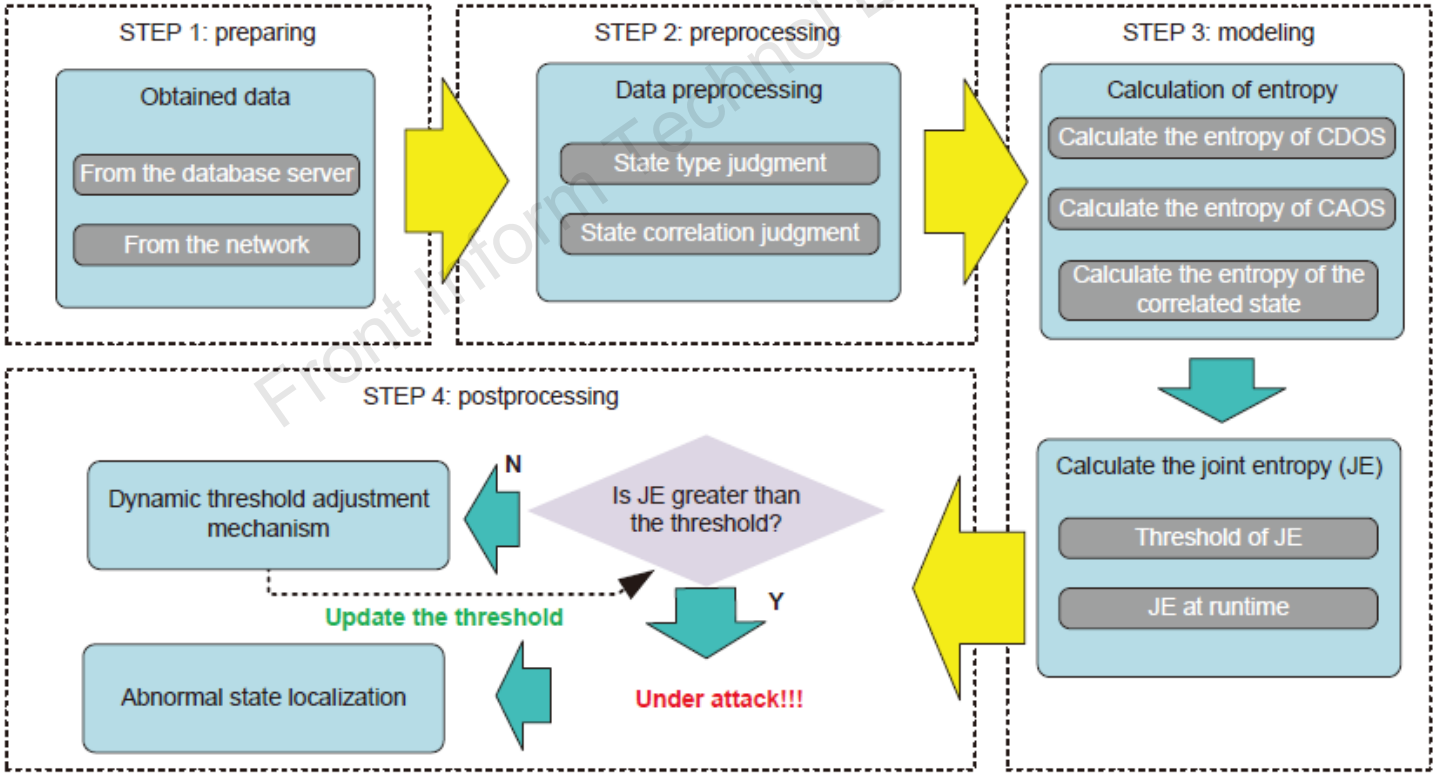
WTS testbed

- The two-stage WTS testbed includes two programmable logic controllers (PLCs) and more than 50 measurement points



Method overview

- Entropy-based intrusion detection method (EBID) includes mainly four steps: preparing, preprocessing, modeling, and postprocessing



Method

- Preparing
  - Obtain the controller's output state (COS) data in two ways: exported from human-machine interface (HMI) or database, captured from the network

- Preprocessing
  - Calculate entropy for COS
    - Discrete: $H_{\mathrm{D}}(X) = -\sum_{i=1}^{N} P(a_i)\lg(P(a_i))$
    - Analog: $H_{\mathrm{A}}(\phi_k) = -\int_S f(x)\lg(f(x))\mathrm{d}x$
  - Correlation between two states
    - Calculate the information gain ratio

$$R(\phi_i, \phi_j) = \frac{I(\phi_i, \phi_j)}{\min(H(\phi_i), H(\phi_j))} = \frac{H(\phi_i) - H(\phi_i|\phi_j)}{\min(H(\phi_i), H(\phi_j))}$$

Method (Cont'd)

- Modeling
  - Calculate the joint entropy of the system

$$H_U(\phi_1, \phi_2, \ldots, \phi_M) = \sum_{k=1}^{M} H(\phi_k) - \sum I(\phi_i, \phi_j)$$

  - Calculate the threshold

$$\bar{H}_U = H_U(1+\alpha),\ \alpha \in [0,1]$$

- Postprocessing
  - Dynamic threshold adjustment mechanism (DTAM)

$$\bar{H}_{U_n} = \begin{cases} \bar{H}_{U_0}, & \hat{\sigma} > V \\ (1 - \varepsilon\frac{\hat{\sigma}}{V})\bar{H}_{U_0}, & \hat{\sigma} \leq V \end{cases}$$

  - Abnormal state localization

Algorithm 1 Abnormal state localization method

Input: R, $\gamma(\phi)$, I, U
Output: Set of abnormal states Ω

```
for each state in γ(φ) do
    Flag ← 1
    for each substate in γ(φ) do
        if R(state, substate) > δ then
            Flag ← 0
        end if
    end for
    if Flag == 1 and state not in I then
        Add state to Ω
    end if
end for
for each state1 in γ(φ) do
    for each state2 in γ(φ) do
        if R(state1, state2) > δ and (state1, state2) not in U then
            Add state1 and state2 to Ω
        end if
    end for
end for
```

Major results

- Detection rate (DR) and false positive rate (FPR)

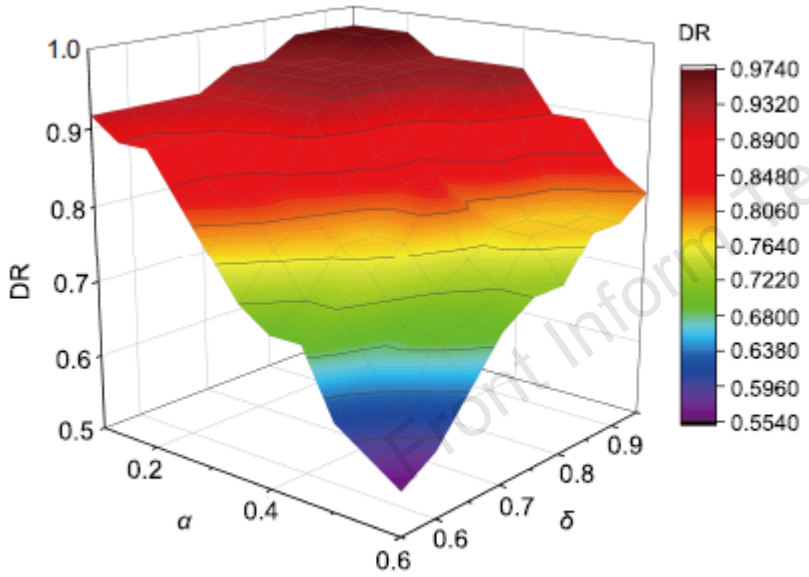


Fig. 7 Detection rate (DR) with different δ's and α's

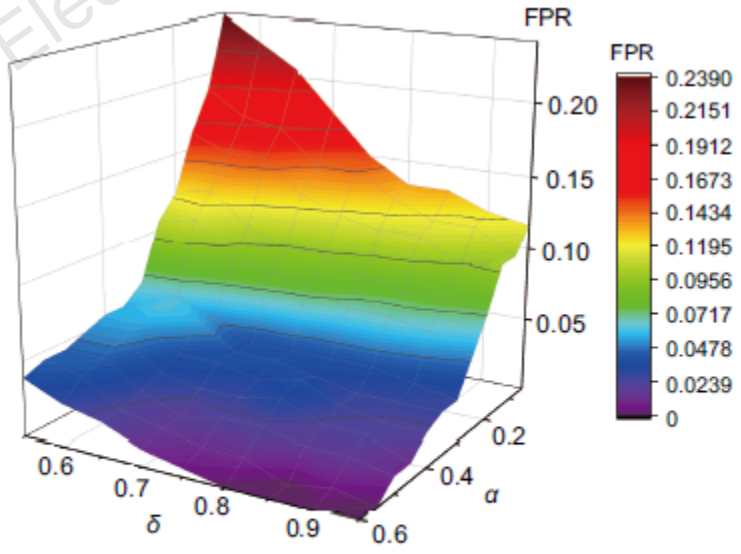


Fig. 8 False positive rate (FPR) with different δ's and α's

Major results (Cont'd)

- Impact of the calculation cycle

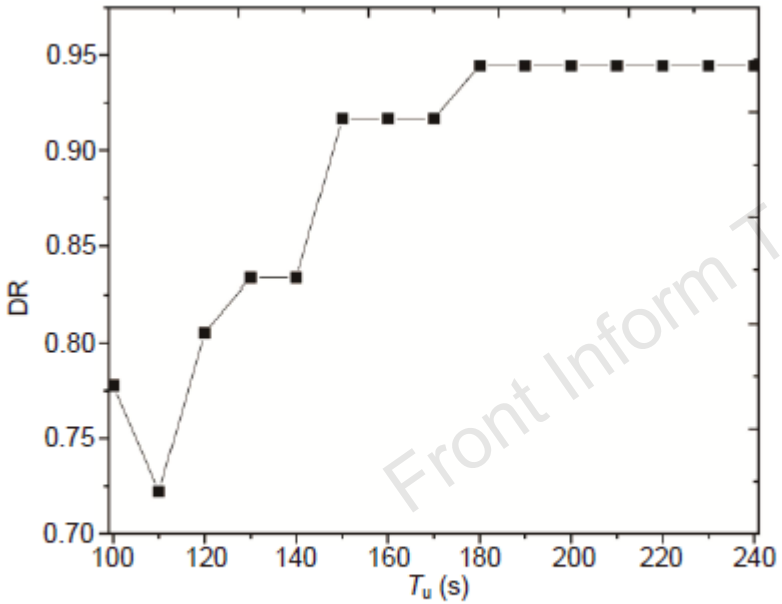


Fig. 10 The varying of the detection rate (DR) with different T_u's

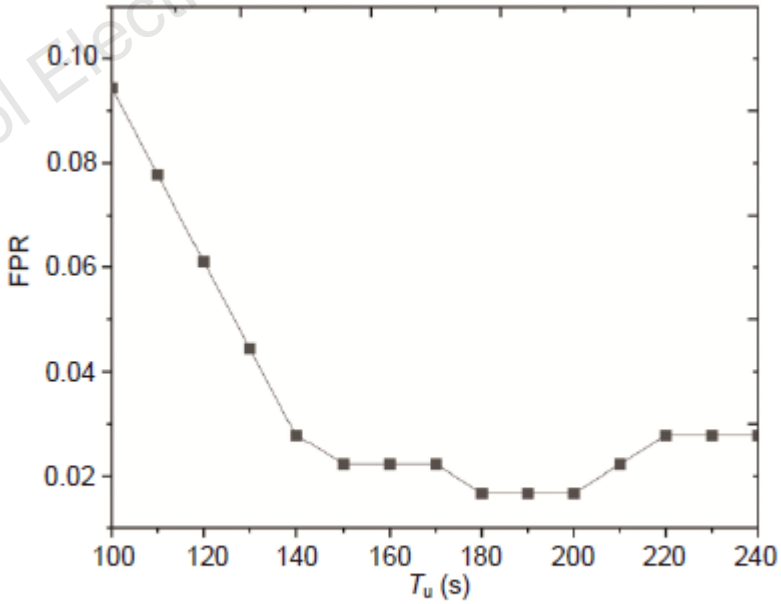


Fig. 11 The varying of the false positive rate (FPR) with different T_u's

Major results (Cont'd)

- Impact of the DTAM

Table 1 The varying of the detection rate (DR) with increasing ε

ε	DR without DTAM	DR with DTAM
0.04	94.44%	94.44%
0.08	94.44%	97.22%
0.12	94.44%	97.22%
0.16	94.44%	97.22%
0.20	94.44%	97.22%

DTAM: dynamic threshold adjustment mechanism

Table 2 The varying of the false positive rate (FPR) with increasing ε

ε	FPR without DTAM	FPR with DTAM
0.04	1.67%	1.67%
0.08	1.67%	1.67%
0.12	1.67%	2.22%
0.16	1.67%	3.33%
0.20	1.67%	6.11%

DTAM: dynamic threshold adjustment mechanism

Conclusions

- In this paper, we presented a novel EBID for intrusion detection by using COSs as input from the WTS. To improve the performance of EBID, we also proposed DTAM and the abnormal state localization method.

- EBID achieved a 97.22% detection rate and 1.67% false alarm rate.

- EBID can be extended to other industrial control systems (ICSs) by adding parsers and encoders of HMI data and network protocols.

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