

REAL-TIME EXTRACTION OF NEUROMORPHIC FEATURES FOR NUCLEAR AND INDUSTRIAL SECURITY

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Rezumat. Monitorizarea instabilităților reactorilor nucleari în timpul operațiunilor de pornire și de regim în sarcină reprezintă o provocare atât pentru securitatea nucleară (controlul reactivității, marjele de oprire), cât și pentru securitatea industrială (detecția anomaliilor în timp real, integritatea buclelor de control). Dintre tipurile de reactoare cele mai vulnerabile la astfel de instabilități neprevăzute, reactoarele de cercetare pulsate și reactoarele modulare mici (SMR) se află în prim-plan. Această lucrare stabilește un cadru independent de tipul reactorului pentru extragerea în timp real a parametrilor exogeni potriviți pentru predictorii neuromorfici Neliniari Autoregresivi Exogeni (NARX). Detaliez în aceasta lucrare un filtru Savitzky-Golay (SG) recursiv în timp real care actualizează coeficienții polinomiali de aproximativ 100 de ori mai rapid decât metoda tradițională. Filtrul SG separă variațiile lente exogene (bare de control, lichid de răcire, presurizatoare) de zgomotul neutronic stochastic. Datele sintetice de reactor SMR relevă ferestre de variație a parametrilor, esențiale pentru agenții TAG (Tool-Augmented Generation) bazați pe NARX.

Abstract. Monitoring nuclear reactor instabilities during start-up and load-following operations challenges both nuclear security (reactivity control, shutdown margins) and industrial security (real-time anomaly detection, control loop integrity). Of the types of reactors most vulnerable to such unanticipated instabilities, pulsed research reactors and Small Modular Reactors (SMR's) are at the forefront. This paper establishes a reactor-agnostic framework for real-time extraction of exogenous parameters suitable for Nonlinear Autoregressive Exogenous (NARX) neuromorphic predictors. I detail a real-time recursive Savitzky-Golay (SG) filter that updates polynomial coefficients ca. $\times 100$ faster than the traditional method. The SG filter decouples exogenous drifts (control rods, coolant, pressurizer) from stochastic neutron noise. Synthetic SMR data shows parameter-swung windows, essential for NARX-based Tool-Augmented Generation (TAG) agents.

Keywords: NARX, SMR, TAG, nuclear reactor instabilities, Savitzky-Golay filter

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1. Introduction

Instability challenges across reactor classes - nuclear reactors, whether pulsed research reactors, conventional power reactors, or Small Modular Reactors (SMR's), exhibit oscillational power fluctuations during start-up and ramp-up phases, load-following operations, transition between natural and forced circulation, reflector or control rod positioning transients.

Power production reactors typically exhibit small fluctuations (20 times smaller than those of fast pulsed facilities), however their smaller class homologues, SMR's intentionally have tighter operational margins in order to maximize economic competitiveness. This renders SMR's more susceptible to instability-reactivities and control challenges.

Nuclear- and industrial-security context - from the instability perspective, unanticipated power oscillations create nuclear security vulnerabilities:

- *reactivity margins*: fluctuations reduce the effective margin for emergency shutdown thresholds,
- *control system stress*: automatic regulators compensate reactively, not proactively,
- *redundancy degradation*: repeated instability episodes stresses protection systems,
- *SMR-specific*: reduced on-site staffing means automated predictive security becomes essential.

In turn, industrial security (focusing on cyber-physical security and control system integrity) is susceptible to nuclear-instabilities, which feed into the its industrial control systems (ICS) and SCADA platforms - as early warnings.

2. SMR particularities

SMR's introduce unique challenges that make prediction of instabilities particularly important:

- *tighter operational margins*: designed for economic competitiveness → less buffer against fluctuations,
- *reduced staffing*: advanced automation → fewer human operators to catch anomalies early,
- *load-following duty*: many SMR designs anticipate load-following → frequent power changes → more instabilities,
- *Passive safety reliance*: while passive systems handle accidents, operational instabilities still challenge control systems
- *Digital I&C proliferation*: SMRs rely heavily on digital instrumentation and control → cyber-security and process security converge

Therefore, for AI control systems to capture the wealth of signals and features, a unified method for quantifying those from raw data stream is needed — to power future NARX-based TAG (Tool-Augmented Generation) agentic models.

For a comprehensive review of data handling in two-phase flow instabilities in SMR steam generators see [6].

3. Real-time feature extraction

Aside from actuator equipment, the foremost signal of interest in nuclear reactor security is neutron noise. To follow this parameter, it must first be deconvoluted from the instantaneous power signal and its modulated rolling baseline. For this I used a Savitzky-Golay (SG) filter [1] due to its robustness (no iterative processes to depend on final initial guesses) and its speed (being an analytical method).

To test the method, I generated a 25 S/s power ramp, with neutron noise based on the frequency profile of the Fourier transform of the point reactor kinetics equations. In this low-frequency region the reactor acts as a low-pass filter to reactivity noise. This is because all designs are dominated in this infra-frequency region by the decay constants of delayed neutron precursors. The longest-lived precursor group typically has a decay constant which corresponds to this infra-frequency range. I additionally added accidental instabilities.

For a window of $2K+1$ bins (in this paper $K=100$ centered at the current bin), the "zero-power" neutron noise will be the residual from a cubic polynomial fit - where the coefficients model the impact of exogenous parameters on the rolling baseline:

$$\sum_{i=-K}^{+K} (Cx_i^3 + Ax_i^2 + Bx_i + D - y_i)^2 = \min \quad 1)$$

To establish the coefficients, I render their derivatives to nil:

$$\sum_{i=-K}^{+K} (Cx_i^3 + Ax_i^2 + Bx_i + D - y_i)x_i^q = 0, \quad q = \overline{0,3} \quad 2)$$

Due to symmetric summation to the left and right of the current point, sums of odd powers vanish, leading to the system of equations:

$$\begin{aligned} CS_6 + BS_4 &= Y_3 \\ AS_4 + DS_2 &= Y_2 \\ CS_4 + BS_2 &= Y_1 \\ AS_2 + D &= Y_0 \end{aligned} \quad 3)$$

where:

$$S_q = \sum_{i=-K}^{+K} x_i^q, \quad Y_q = \sum_{i=-K}^{+K} y_i x_i^q \quad 4)$$

Denoting $\lambda_4 = S_4/S_2$, the solution to the system is:

$$\begin{aligned} C &= \frac{Y_3/\lambda_4 - Y_1}{S_6/\lambda_4 - S_4} \\ A &= \frac{Y_2/S_2 - Y_0}{\lambda_4 - S_2} \\ B &= \frac{Y_1 S_6 / (\lambda_4 S_2) - Y_3}{S_6/\lambda_4 - S_4} \\ D &= Y_0 - A S_2 \end{aligned} \quad 5)$$

Given the ramp-up feature, or in general unknown reactor power, I use the dimensionless ratios B/D and C/D to decouple exogenous drifts from neutron noise. Under stable operation these ratios have a negligible noise pattern. For an SMR-like context however, they display detectable swings 30-70 s before peak power excursion - a narrow but still quite actionable window for NARX prediction.

While for a single point the solution is fast, note that modern DAQ systems acquire data from a variety of sensors at up to 100 kS/s. Therefore, the direct solution becomes computationally intensive. For real-time monitoring, I designed a recursive procedure that reuses calculations from the previous point. For a new data point y_{next} replacing y_{last} , the updates are:

$$\begin{aligned} Y'_0 &= Y_0 + (y_{\text{next}} - y_{\text{last}}) \\ Y'_1 &= Y_1 - Y_0 + (2K + 1)(y_{\text{next}} + y_{\text{last}}) \\ Y'_2 &= Y_2 - 2Y_1 + Y_0 + (2K + 1)^2(y_{\text{next}} - y_{\text{last}}) \\ Y'_3 &= Y_3 - 3Y_2 + 3Y_1 - Y_0 + (2K + 1)^3(y_{\text{next}} - y_{\text{last}}) \end{aligned} \quad 6)$$

where Y'_k are the sums at the current point, expressed in terms of those from the previous point. This translation is possible because moving one step forward corresponds to updating $y_i(i-1)^q$ relative to $y_i i^q$, which can be expressed using all previously known power sums. Thus, for high-order Savitzky-Golay polynomials and large $2K+1$ context windows, rapid updates in real-time for pedestal monitoring are possible for a large array of simultaneously tracked quantities. The goal of exogenous influence extraction is to uncover the trends that move the baseline. As such I perform a $2K+1$ average of B/D and C/D to eliminate any local fluctuations.

Computational gain: direct SG is O_K per sample, my recursive SG is just O_1 . Given a typical $K=100$, this translates into a factor $\times 100$ faster — enabling real-time deployment in a signal-rich SMR environment. Recent work [7] demonstrates

real-time Savitzky-Golay filtering on FPGA hardware at 192 Hz with only 260 μ W power consumption, confirming feasibility for embedded SG deployment.

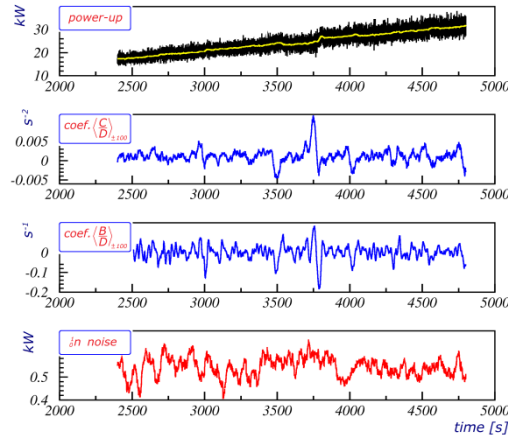


Fig.1. Synthetic SMR power trace (25 S/s). Top: neutron noise (black - as kW power swing) with SG trace (yellow - D coefficient). Middle two panels: $\langle \frac{C}{D} \rangle_{\pm 100}$ and $\langle \frac{B}{D} \rangle_{\pm 100}$ averaged over 201 samples. Note their swing shortly (20–70 s) prior to power excursion. Lower panel: "zero-power" neutron noise - essentially no correlation to exogenous influences driving the instabilities.

Conclusions

The recursive Savitzky-Golay filter extracts self-scaling parameters at an OI computational complexity cost. The parameters used display swing windows 30-70 s before power excursion in synthetic SMR data. This is sufficient for a NARX neuromorphic predictor to act as a perceptron for a TAG AI-security agent.

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