Real-time implementation in JET of the SPAD disruption predictor using MARTe

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Introduction

• Context: Current (and future) Tokamak devices
• Plasma disruptions are unavoidable and damage the machine
  • Electro-Magnetic Forces
  • Thermal Loads
  • Runaway Electrons
• Mitigation techniques must be applied before the disruption occurs -> Disruption Predictors
• Several approaches already exist:
  • Threshold based predictor -> Limit set manually based on the risk
    • Using Locked Mode, Plasma Current, or Restraint Ring Loop
    • Optimal/Universal threshold?
  • APODIS -> Machine Learning (SVM).
    • Using **seven** signals (including Locked Mode and Plasma Current)
    • Need training based on disruptive and non-disruptive discharges
    • Machine dependant?
    • New/Upgraded machines?
    • Big changes in plasma parameters?
    • Difficult to find physics explanation justifying the detector classification
Introduction: MARTe

• MARTe: Multi-threaded Application Real-Time executor
  • Multiplatform framework for implementing real-time applications
  • Isolation
    • From PC hardware & OS
    • From system I/O software
  • Modularity

• Already used in several tokamaks (RFX, COMPASS, ISTTOK, FTU)
  • Also in JET: Interface with JPF/RTDN already implemented

Code reuse + maintainability
Introduction: MARTe

- MARTe applications consist of *Threads* periodically executing *GAMs* (Generic Application Modules)
- GAMs are interconnected using Dynamic Data Buffer (DDB)
- Typical GAMs:
  - Timing (Thread clock)
  - System I/O
    (JETs: Read/Write from/to RTDN/JPFs)
  - Process GAMs
  - Thread-to-Thread communication (DDB-to-DDB)
SPAD Disruption Predictor

- **SPAD**: Single signal Predictor based on Anomaly Detection

- Objectives:
  - No use of data from past discharges -> No training needed

- Method
  - Use Locked Mode signal -> Highly related with disruptions
  - Detect abnormal behavior in the signal
    - Normal behavior is learnt from the beginning of the discharge
  - Predict disruptions using only one signal
  - Easy to understand explanation for detection
SPAD Disruption Predictor

- Already presented

- Implemented in MATLAB and not suitable for real-time.
SPAD: Algorithm

\[
\text{LockedMode}_{\text{signal}}[k] = LM[k]
\]

Sliding Windows

\[
W[k] = (LM[k - 31], \ldots, LM[k])
\]

Haar Wavelet Transform

\[
H_{L2}(W[k]) = (H_{App}[k], H_{Det}[k]) = ((H_{App0}[k], \ldots, H_{App7}[k]), (H_{Det0}[k], \ldots, H_{Det23}[k]))
\]

Mahalanobis Distance

\[
D_M(H_{App}[k], H_{App}[0..k-1]) = D_M[k]
\]

Outlier Factor Function

\[
O_F(D_M[k], D_M[0..k-1]) = O_F[k]
\]

Alarm Criteria

\[
\text{SPAD}_{\text{Alarm}}(O_F[k], LM[k]) = \text{SPAD}_{\text{Alarm}}[k] \in \{0,1\}
\]
• Each step is performed in a different GAM
  • + GAM to signal start based on Plasma current threshold
• One single thread executing all the GAMS
• Thread execution period = 1ms
• Problems
  • Covariance Matrix
  • Standard Deviation
  • Mean

Of a set growing with each iteration

Execution time not bounded
“Update” the values, no recalculate
SPAD: Real-time Implementation SlidingWindowGAM

- Provide the latest 32 values (window) of Locked Mode signal
- Update the window every 2 thread cycles (2 ms) (slide)
- Signals when the window has been updated

Parameters:
- Input signal
- Window size
- Window slide

LockedMode\text{signal} [k] = LM[k]

Sliding Windows

\[ W[k] = (LM[k - 31], ..., LM[k]) \]
\[ W[k + 1] = W[k] \]
\[ W[k + 2] = (LM[k - 29], ..., LM[k + 2]) \]
• Calculate the Haar Wavelet Transform Approximation Coefficients (for SPAD Level 2 $H_{L2}: \mathbb{R}^{32} \rightarrow \mathbb{R}^8$)

• Optimizations
  • Coefficients not calculated by iteration

• Parameters:
  • Input signal
  • Level applied

$W[k] = (LM[k - 31], ..., LM[k])$

$H_{L2}(W[k]) = (H_{App}[k], H_{Det}[k])$

$((H_{App0}[k], ..., H_{App7}[k]), (H_{Det0}[k], ..., H_{Det23}[k]))$

$W[k] = (LM[k - 31], ..., LM[k])$

$H_{App1,i} = \sqrt{2}(x_{2i} + x_{2i+1})/2$

$H_{App2,i} = \sqrt{2}(H_{App1,2i} + H_{App1,2i+1})/2$

$H_{AppX,Y} = (\sqrt{2})^{X\%2} \sum_{i=Y2^X}^{(Y+1)2^X} x_i / 2^\left[\frac{X}{2}\right]$
• $H_{\text{App}}$ used as feature vector
• Calculate distance between current vector and centroid of the cluster formed by all past vectors in the discharge.

**Optimizations**

• Covariance Matrix ($S$) and mean vector ($\mu$) “updated”
  • Store partial sums and products
• LUP method used for inverse product
  • Can be done better!

$$H_{L2\text{App}} (W[k]) = (H_{\text{App}0}[k], \ldots, H_{\text{App}7}[k])$$

Mahalanobis Distance

$$D_M(H_{\text{App}}[k], H_{\text{App}}[0..k-1]) = D_M[k]$$

$$D_M(x, X) = \sqrt{(x - \mu_X)^T S_X^{-1} (x - \mu_X)}$$
• Is the current vector anomalously far from the cluster?
• Factor given by an equation using mean($\mu$) and standard deviation($\sigma$) from all past distances in the discharge.
• Optimizations
  • Update mean and standard deviation storing partial sums and products

\[
O_F[k] = \left| \frac{D_M[k] - \mu(D_M[0..k])}{\sigma(D_M[0..k])} \right|
\]

\[
D_M(H_{App}[k], H_{App}[0..k - 1]) = D_M[k]
\]

Outlier Factor Function
SPAD: Real-time Implementation

SPADA\textsubscript{Alarm}GAM

• Trigger the disruption alarm if the conditions are met
  • Outlier factor surpasses a configurable threshold
  • Current value of Locked Mode is a global maxima

• Analysis over all ILW campaigns shows that K=10 works fine

• Parameters
  • Outlier Factor Threshold

\[
O_F(D_M[k], D_M[0..k-1]) = O_F[k]
\]

Alarm Criteria

\[
SPAD_{\text{Alarm}}(O_F[k], LM[k]) = SPAD_{\text{Alarm}}[k] \in \{0,1\}
\]

\[
SPAD_{\text{Alarm}}[k] = (LM[k] === \text{max}(LM[0..k])) \&\& (O_F[k] > K)
\]
Results

• Same detection results than non-optimized MatLAB reference application.
• Execution time bounded during the whole discharge.
• Tested using JETs JPF data from all safe and unintentional disruptive discharges with ILW from 2011 to 2014 (C28-C34)
  • 1738 safe discharges
  • 566 unintentional disruptive discharges

<table>
<thead>
<tr>
<th>Predictor</th>
<th>False Alarms</th>
<th>Missed Alarms</th>
<th>Tardy Detections</th>
<th>Valid Alarms</th>
<th>Premature Alarms</th>
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<tr>
<td>SPAD</td>
<td>7.42%</td>
<td>10.60%</td>
<td>3.18%</td>
<td>83.57%</td>
<td>2.65%</td>
</tr>
<tr>
<td>APODIS</td>
<td>&lt;5%</td>
<td>15.38%</td>
<td>2.47%</td>
<td>79.15%</td>
<td>3.00%</td>
</tr>
<tr>
<td>LMPT</td>
<td>---</td>
<td>30.39%</td>
<td>3.00%</td>
<td>63.69%</td>
<td>2.65%</td>
</tr>
</tbody>
</table>
Results

- Execution time in a **no-Real Time** platform
- 4 cores, 2 threads/core, 3.6 GHz, 16 GB RAM, RHEL 6.5
- Confidence Level 97% (Mean Time + 3·Standard Deviation)
- Max execution time 26.9280 us (OS interruptions?)
Conclusions

• Implemented real-time disruption predictor in MARTe
• Execution time per cycle << 1ms (even in no-RT platforms)
• Optimizations for the calculation of Covariance Matrix, Standard Deviation and mean
  • Execution time bounded for the whole discharge
  • Depends only on the size of the feature vector (not on the duration of the discharge!!)
• Identical detection results for MatLAB reference application and MARTe implemented predictor.
Future Work

• Predictor:
  • Reduce false alarms
  • Improve detection ratio
  • Study behavior with other/more signals
    • Related with root of disruption

• Implementation
  • Real-time implementation of the improvements in the predictor
  • Improve inverse matrix and vector-matrix-vector product performance (Not really important due to current performance)
Thanks for your attention