MATLAB EXPO 2019

APM기반의 자기진단:
반도체공정용 진공펌프 상태진단의 새로운 지평

한국표준과학연구원 / 역학센터
정 완 섭

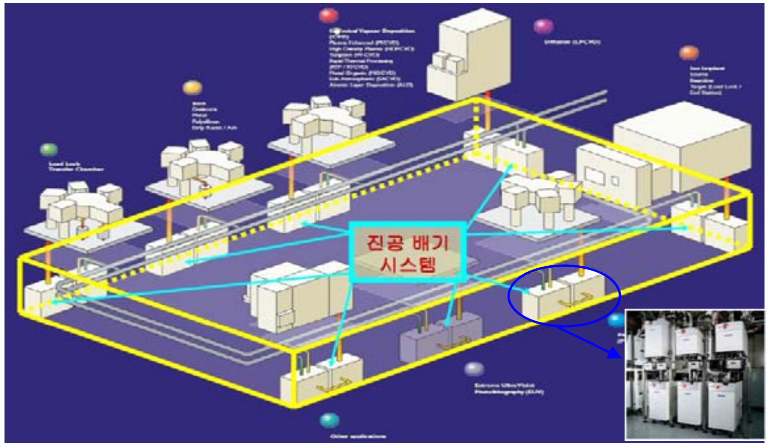
KRISS

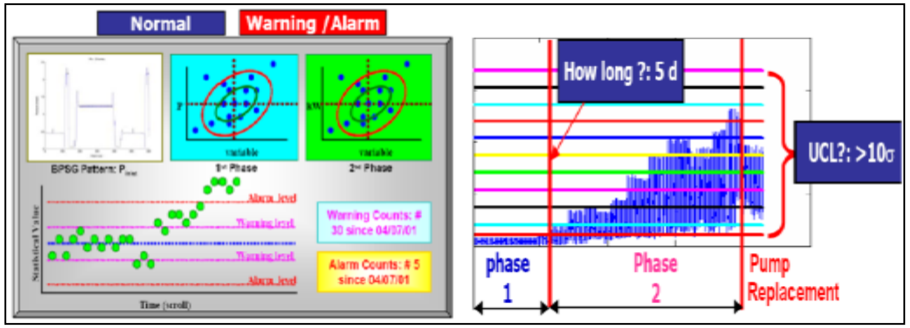
목차

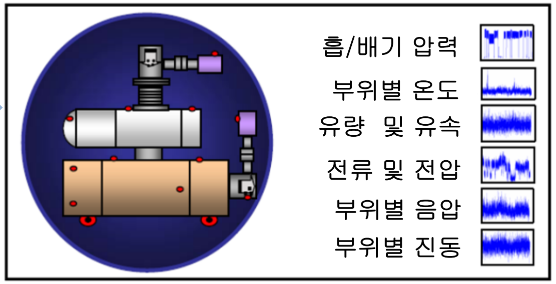
발표자 소개

- 한국표준과학연구원, 역학 센터 책임연구원 (1984~현재)
- UST 측정 과학 교수
- 영국 University of Southampton (ISVR) 박사 (1993)
  - Neural Network 기반의 비선형 시스템 제어
- 제 23대 한국음향학회 회장 (2017)
- 학술활동: 한국음향학회, 한국소음진동공학회, 대한기계학회, 한국진공학회, 등
- 관심분야: AI 모델 기반의 신호처리 (반도체 공정 진공펌프 상태 진단 및 예지 보수), 수중 음향 다채널 소나 (고 해상도 영상, InSAS), 차세대 IMU & 실시간 Kalman 필터 구현 등

국내 반도체 산업 지원 국책과제 (2008 ~ 2013):
"Smart 진공 배기 시스템 개발"

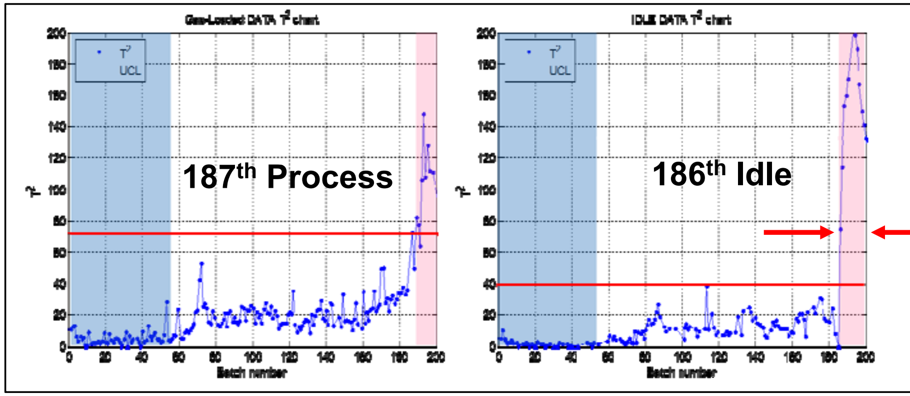






SPM (or VPC)
제품화

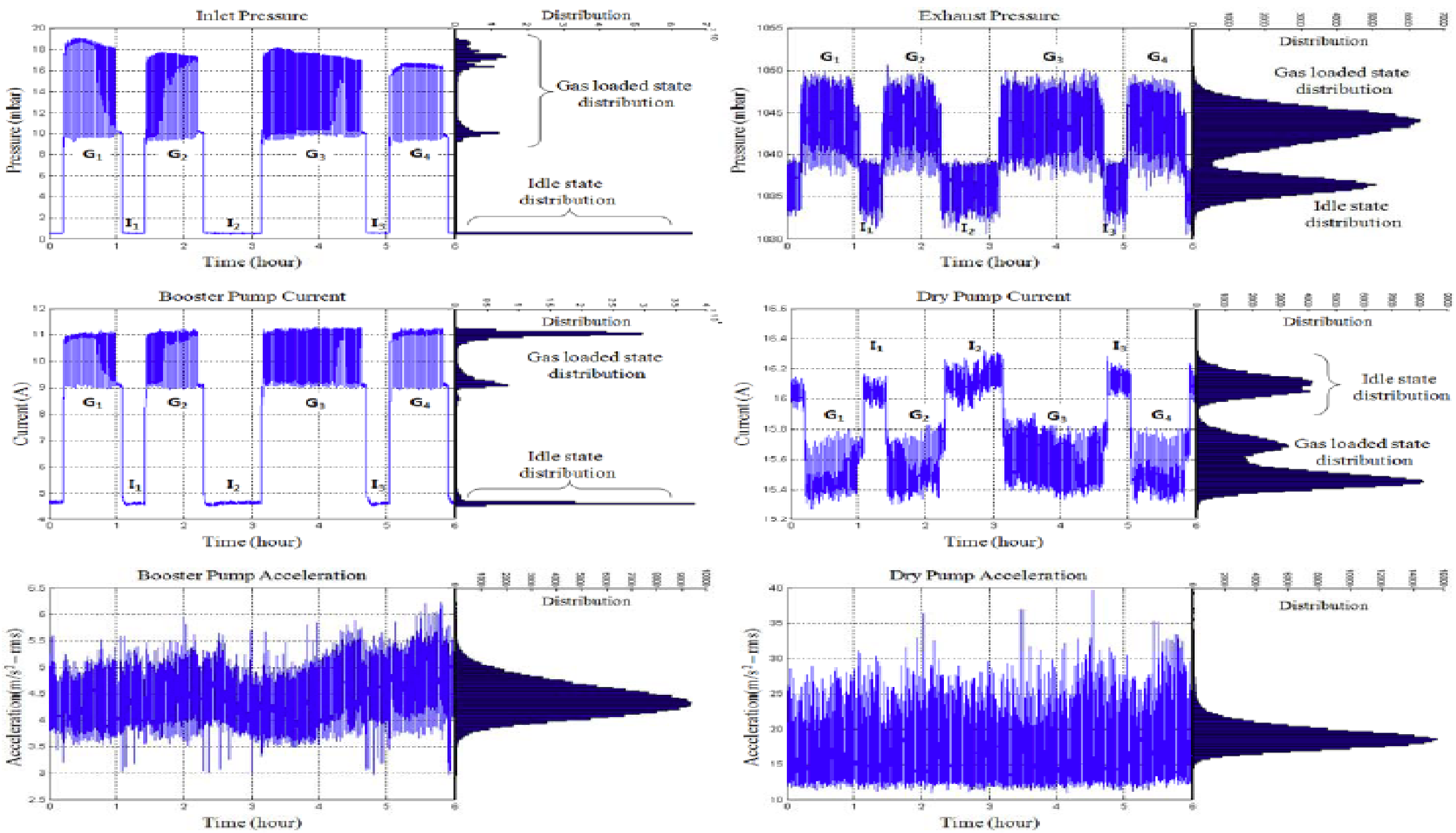
PM 주기 설정
기술



14 공정
후 정지

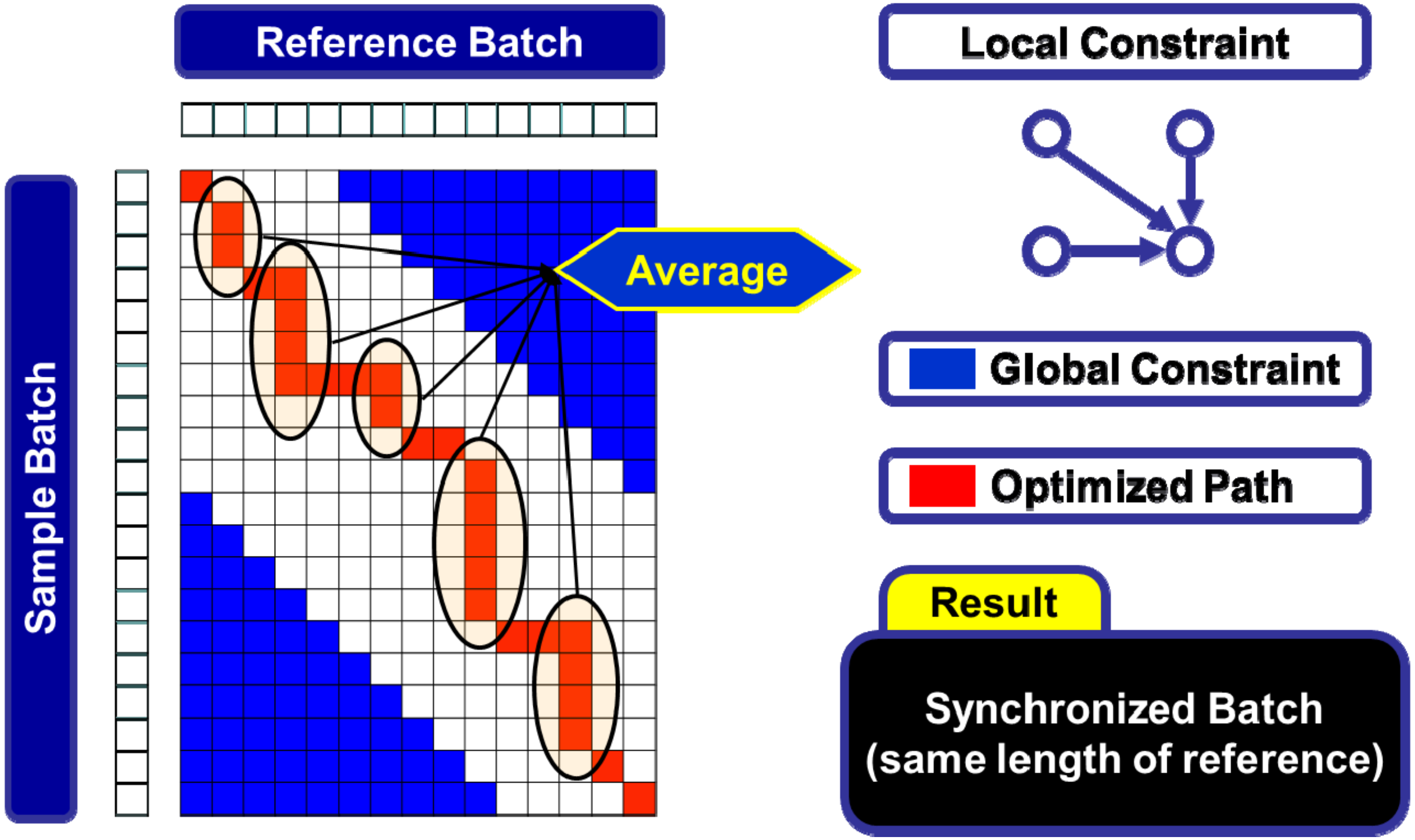
- 2 PCT Patents: Registered in Korea, USA, Japan, China, EU
  - Precision diagnostics and predictive maintenance (PM)

반도체 공정용 진공펌프 상태변수들의 분포 특성



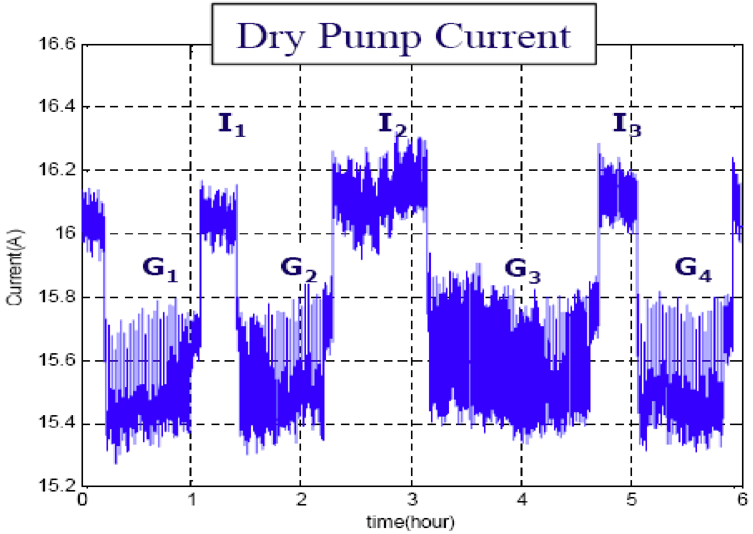
➤ **Technical challenges, neither simple pictures nor simple statistical models.**

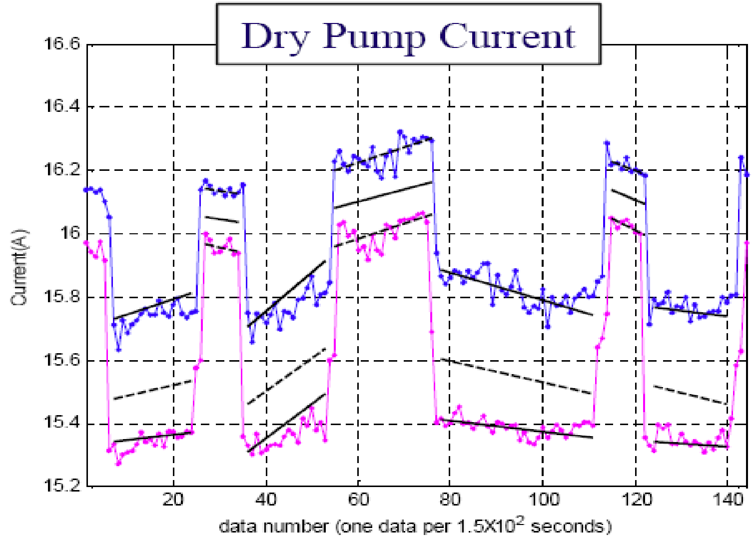
공정별 변수 길이 조정: Dynamic Time Wrapping



➢ **DTW Scheme: Huge computation load, proper for GPU but not DSP.**

적응형 인자 모델 (Adaptive Parametric Model, APM)



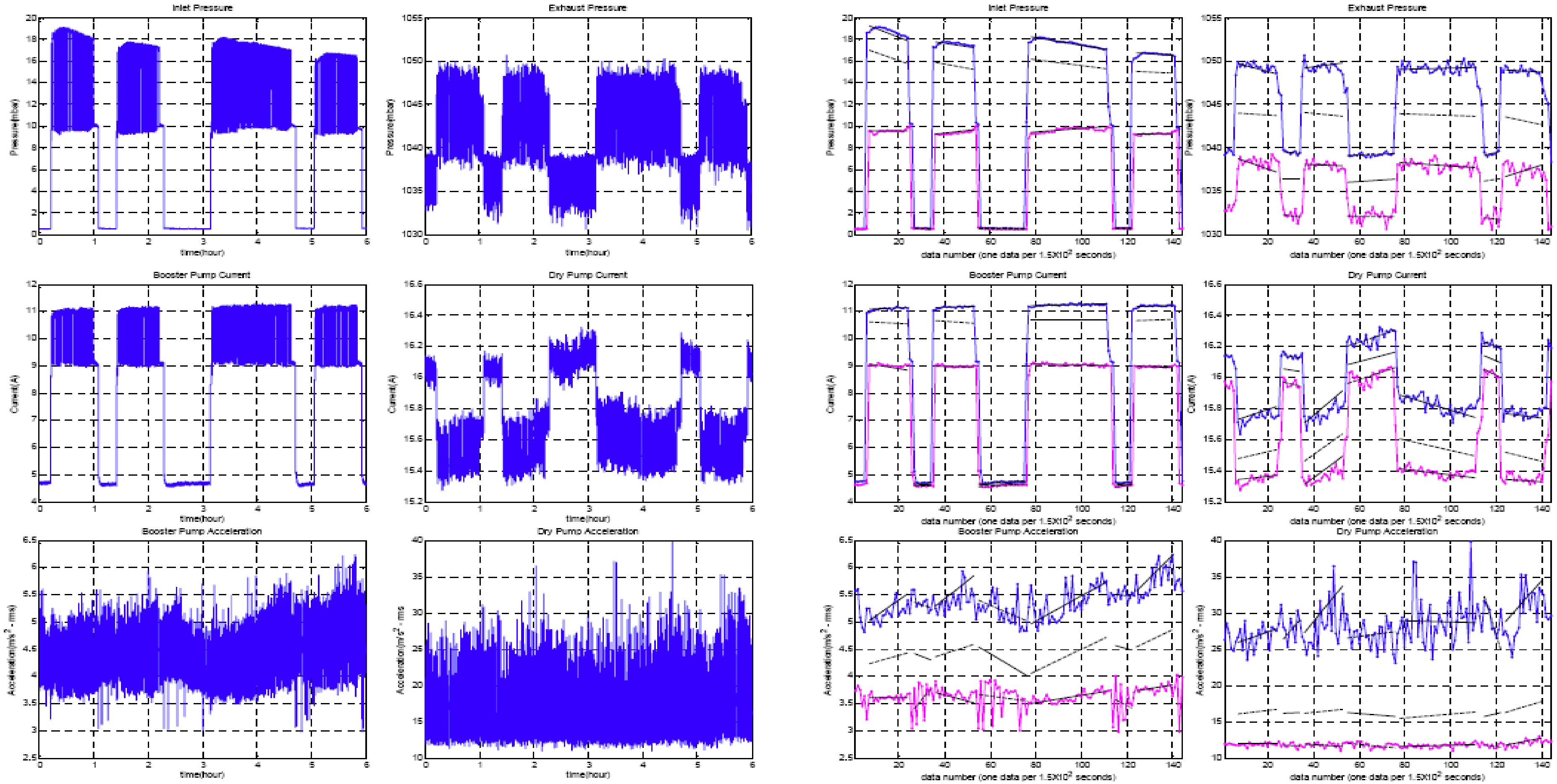


$$y_{k,n} = a_k \cdot n + b_k$$

$$a_k = \frac{N \cdot \sum_{n=1}^{N} n \cdot y_{k,n} - \sum_{n=1}^{N} n \cdot \sum_{n=1}^{N} y_{k,n}}{N \cdot \sum_{n=1}^{N} n^2 - \left(\sum_{n=1}^{N} n \right)^2} \qquad b_k = \frac{\sum_{n=1}^{N} n^2 \cdot \sum_{n=1}^{N} y_{k,n} - \sum_{n=1}^{N} n \cdot \sum_{n=1}^{N} n \cdot y_{k,n}}{N \cdot \sum_{n=1}^{N} n^2 - \left(\sum_{n=1}^{N} n \right)^2} \qquad \sigma_k = \sqrt{\frac{1}{N} \sum_{n}^{N} (y_{k,n} - a_k \cdot n - b_k)^2}$$

- **APM Capability is tracking the mean trend (a·n+b) and the standard deviation σ of each separable distribution of state variables**

적응형 인자 모델 (APM)과 재구성된 상태변수



➢ **What about graphical trend analysis?**

추정된 적응형 인자 모델 (APM) 값의 테이블

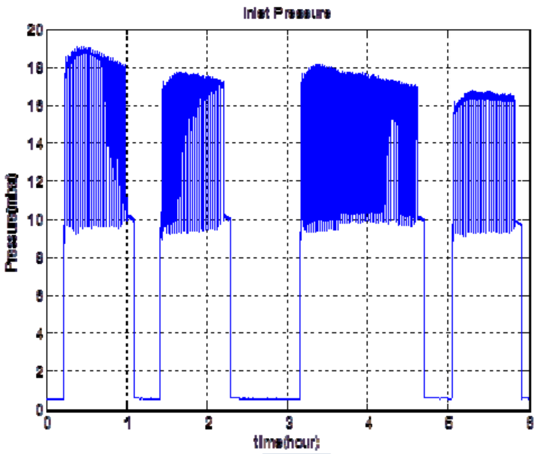
- Exhaust pressure difference values
  : 7.1 mbar (Initial)
  7.6 mbar (Last)
- Mean value of supply current (BP)
  Load : 8.2 A (Initial)
  8.9 A (Last)
  Idle : 4.3 A (Initial)
  3.9 A (Last)
- Mean value of supply current (DP)
  Load : 15.8 A (Initial)
  15.8 A (Last)
  Idle : 16.2 A (Initial)
  16.5 A (Last)
- Vibration Level
  Mean : 24 % Increment
  Peak : 5.8% Increment
- Acoustic Noise Level
  Mean : 26 % Increment
  Peak : 99% Increment

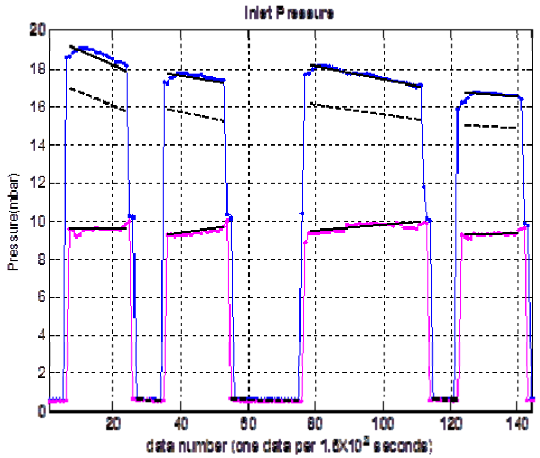
Pump Operation Conditions			Step 1 Gas-Loaded State 1	Step 2 Idle State1
Inlet Pressure [mbar]	Mean Value		20.3	0.75
	Upper Bound	a_U	0.084	-0.003
		b_U	19.3	0.77
		Peak	21.4	1.06
	Lower Bound	a_U	0.086	-0.002
		b_U	19.1	0.73
BP Supply Current [A]	Mean Value		8.93	3.86
	Upper Bound	a_U	0.015	-0.003
		b_U	8.79	3.98
		Peak	9.19	4.10
	Lower Bound	a_U	0.015	-0.003
		b_U	8.67	3.91
Vibration Level on DP [m/s²]	Mean Value		13.9	13.8
	Upper Bound	a_U	-0.033	0.0056
		b_U	16.3	15.5
		Peak	16.7	16.3
	Lower Bound	a_U	-0.002	12.2
		b_U	-0.002	12.3

Pump Operation Conditions			Step 1 Gas-Loaded State 1	Step 2 Idle State1
Exhaust Pressure [mbar]	Mean Value		1014.9	1007.3
	Upper Bound	a_U	-0.024	0.009
		b_U	1018.1	1009.8
		Peak	1018.5	1010.8
	Lower Bound	a_U	-0.001	0.021
		b_U	1012.0	1003.7
DP Supply Current [A]	Mean Value		15.8	16.5
	Upper Bound	a_U	-0.002	0.002
		b_U	16.0	16.6
		Peak	16.0	16.7
	Lower Bound	a_U	0.0000	0.0004
		b_U	15.7	16.4
Acoustic Noise Level [Pa]	Mean Value		1.07	1.02
	Upper Bound	a_U	-0.011	-0.003
		b_U	1.99	1.75
		Peak	2.29	2.63
	Lower Bound	a_U	-0.001	0.0004
		b_U	0.75	0.73

➢ **What about quantitative trend analysis?**

적응형 인자 모델 (APM)의 특징





pump operation (time)			process 1 (3150s)	process 2 (3150s)	process 3 (5850s)	process 4 (3300s)
variable	region	symbol				
Inlet Pressure [mbar]	upper bound.	a_u	-0.08003	-0.03128	-0.03571	-0.0161
		b_u	19.217	17.773	18.226	16.766
		σ_u	0.039051	0.034187	0.048675	0.02256
	lower bound.	a_l	0.001968	0.024049	0.015727	0.001189
		b_l	9.5477	9.2433	9.4297	9.29
		σ_l	0.019503	0.033994	0.1374	0.03503
	Mean	a_m	-7.20E-02	-4.04E-02	-2.53E-02	-1.09E-02
		b_m	16.987	15.905	16.156	15.081
		σ_m	0.30622	0.32314	0.52289	0.4862

공정주기 ≈ 1^h

	4개월 누적 DATA(5case)	
분류	10Hz RMS DATA	APM 시계열 DATA
용량	약 5.9 GB	약0.35 GB
매체	CD 9장	CD 1장

데이터 압축율 ≈ 75

- 주기 **8**시간 **LDO** 공정에서 **1,000** 배 이상 데이터 압축 율 구현

적응형 인자 모델 데이터 구조체 만들기

- **Batch Data structure: "Standard database" model**
  - **Gas Loaded States & Idle States: Old Model of Data Structure**

$$X_{IP,GL} = \begin{bmatrix} a_{u1} & b_{u1} & \sigma_{u1} & a_{l1} & b_{l1} & \sigma_{l1} \\ a_{u2} & b_{u2} & \sigma_{u2} & a_{l2} & b_{l2} & \sigma_{l2} \\ a_{u3} & b_{u3} & \sigma_{u3} & a_{l3} & b_{l3} & \sigma_{l3} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{uj} & b_{uj} & \sigma_{uj} & a_{lj} & b_{lj} & \sigma_{lj} \end{bmatrix}$$

Batch Number

$$X_{IP,ID} = \begin{bmatrix} a_1 & b_1 & \sigma_1 \\ a_2 & b_2 & \sigma_2 \\ \vdots & \vdots & \vdots \\ a_j & b_j & \sigma_j \end{bmatrix}$$

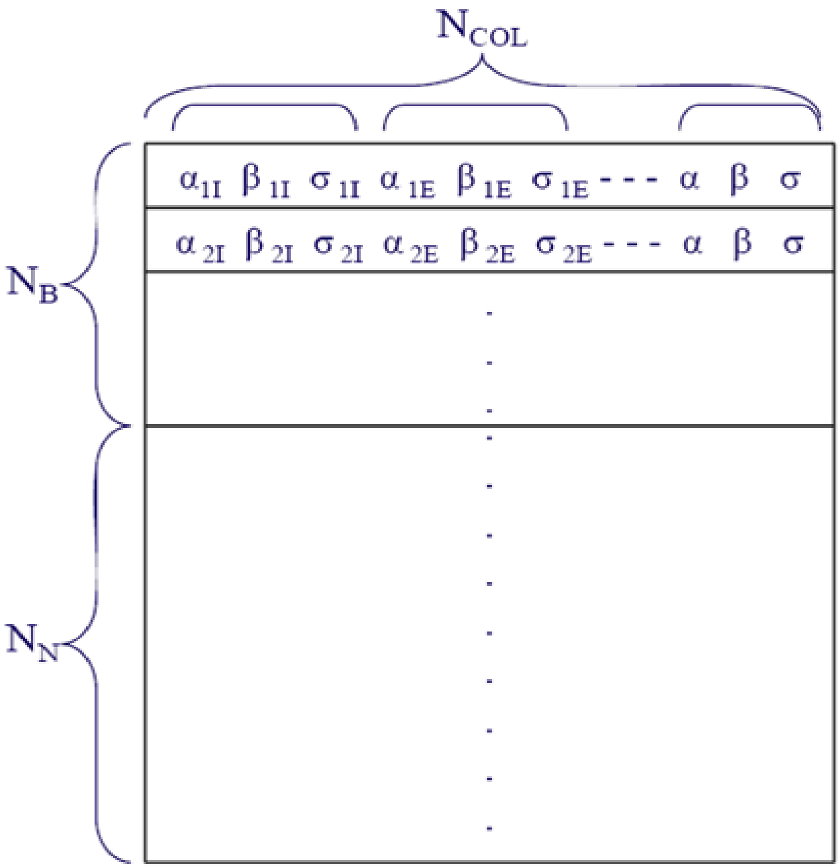
  - 전체 상태변수에 대한 **Batch Data of j Processes (2D Data Structure)**

$$\mathbf{X}_{GL} = \begin{bmatrix} X_{IP,GL} & X_{EP,GL} & X_{BC,GL} & X_{DC,GL} & X_{BA,GL} & X_{DA,GL} & \bullet\bullet\bullet\bullet\bullet\bullet \end{bmatrix}^T$$

$$\mathbf{X}_{ID} = \begin{bmatrix} X_{IP,ID} & X_{EP,ID} & X_{BC,ID} & X_{DC,ID} & X_{BA,ID} & X_{DA,ID} & \bullet\bullet\bullet\bullet\bullet\bullet \end{bmatrix}^T$$

Each column corresponding to one process batch data &
a number of columns corresponding to the number of process batches.

적응형 인자 모델 데이터 구조체



- N_{col} : 단위 공정별 **APM** 인자 수
- N_B **: NOC (Normal Operation Condition)** 공정 수
- N_N **:** 상태 진단을 수행 공정 수

➢ **Separated “Idle” & “Gas-Loaded” APM Databases**

정상상태의 기준 배치 데이터: 고유 특징 추출

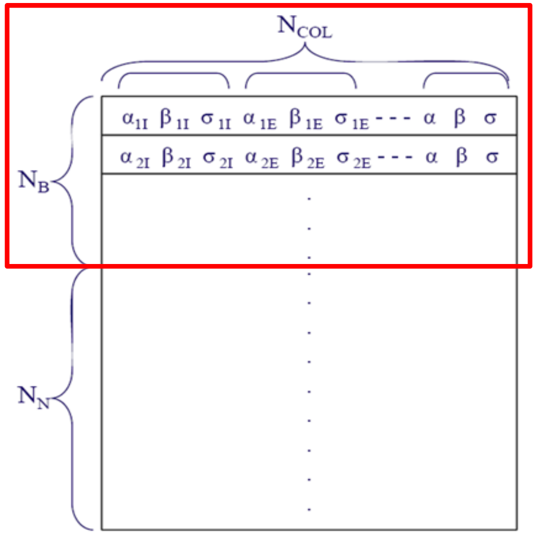
■ 정상운전상태 (Normal Operating Conditions, NOC) Batch Data

- ➢ NOC Batch Data: Collected in the Gas-Loaded & Idle States (GLS & IDS) of the First 7 ~ 35 Process Days (Normally, N_{NOC} = 100 ~ 500 Process Batches)

$$\mathbf{X}_{NOC,GL} \quad \& \quad \mathbf{X}_{NOC,ID}$$

- ➢ Singular Value Decomposition (SVD) of NOC Batches:

$$\mathbf{X}_{NOC} = \mathbf{U}\boldsymbol{\Lambda}\mathbf{V}^T = \mathbf{U}_S\boldsymbol{\Lambda}_S\mathbf{V}_S^T + \mathbf{E} \Leftarrow \mathbf{E} = \sum_{i=N_S+1}^{N_{NOC}} \Lambda_i \mathbf{u}_i \mathbf{v}_i^T$$



- U_S: Column-orthogonal matrix selected from N_S significant SVs
- Λ_S: Diagonal matrix (N_S significant SVs)
- V_S: Column-orthogonal matrix selected from N_S SVs
- E: Residual (noise space) components of NOC batch data

현 공정 데이터와 정상 공정 데이터 (NOC) 비교

Comparison between k-th Process Batch & NOC Batches:

- Projecting the k-th process batch data $\mathbf{x}_k$ to the NOC batch:

$$\mathbf{t}_k = \mathbf{x}_k^T \mathbf{U}_S$$

- Calculating the Hotelling's T^2 (Similarity): "1st Statistic"

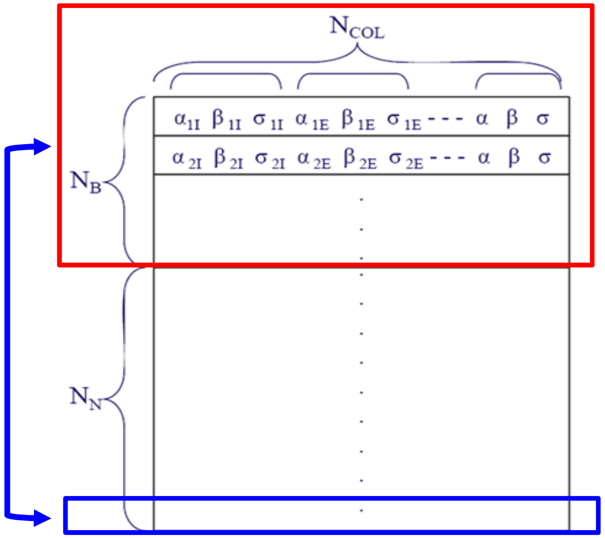
$$T_k^2 = \mathbf{t}_k \mathbf{S}^{-1} \mathbf{t}_k^T \qquad \mathbf{S} = \frac{1}{N_{NOC}-1} diag\left[\Lambda_1^2 \quad \Lambda_2^2 \quad \bullet \quad \bullet \quad \bullet \quad \Lambda_{N_S}^2\right]$$

- Calculating the k-th batch residual:

$$\mathbf{e}_k = \mathbf{x}_k - \mathbf{U}_S \mathbf{t}_k$$

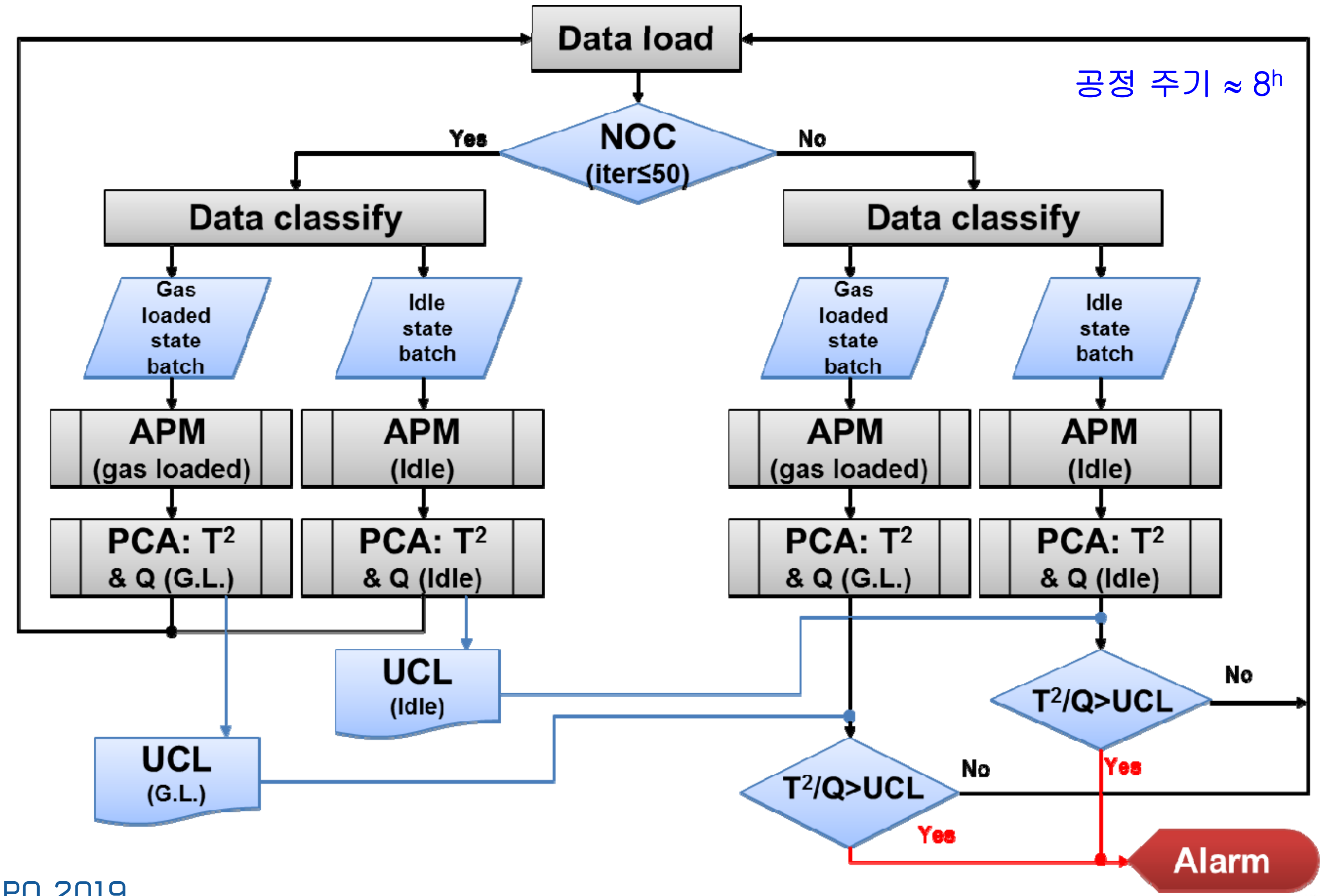
- Calculating Sum of Squared Residuals Q (Difference): "2nd Statistic"

$$Q_k = \mathbf{e}_k^T \mathbf{e}_k$$



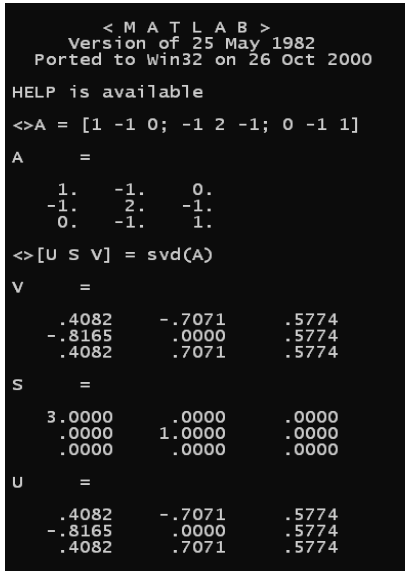
k-th Process Batch

T^2와 Q 기반의 자기진단 흐름도: LTO 공정 예



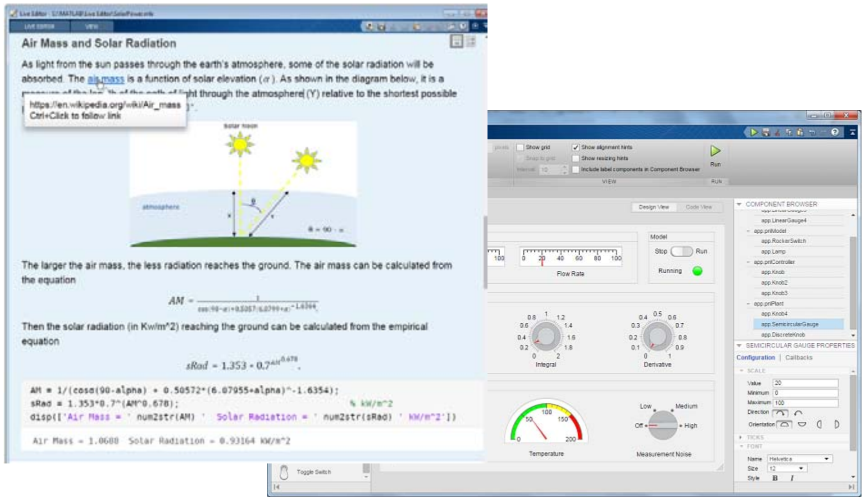
MathWorks 솔루션을 프로젝트에 적용한 이유

- MATLAB은 행렬기반의 언어로 직관적으로 쉬운 데이터 분석 및 수학적 모델링 구현



```
        < M A T L A B >
     Version of 25 May 1982
  Ported to Win32 on 26 Oct 2000

HELP is available

<>A = [1 -1 0; -1 2 -1; 0 -1 1]

A     =

     1.    -1.     0.
    -1.     2.    -1.
     0.    -1.     1.

<>[U S V] = svd(A)

V     =

     .4082    -.7071     .5774
    -.8165     .0000     .5774
     .4082     .7071     .5774

S     =

    3.0000     .0000     .0000
     .0000    1.0000     .0000
     .0000     .0000     .0000

U     =

     .4082    -.7071     .5774
    -.8165     .0000     .5774
     .4082     .7071     .5774
```

- MATLAB은 수치 해석 분야의 산 역사이며 선형 대수학의 표준 함수들(libraries)을 제공.



- 엔지니어와 과학자에게 최적화된 연산 도구들 제공.

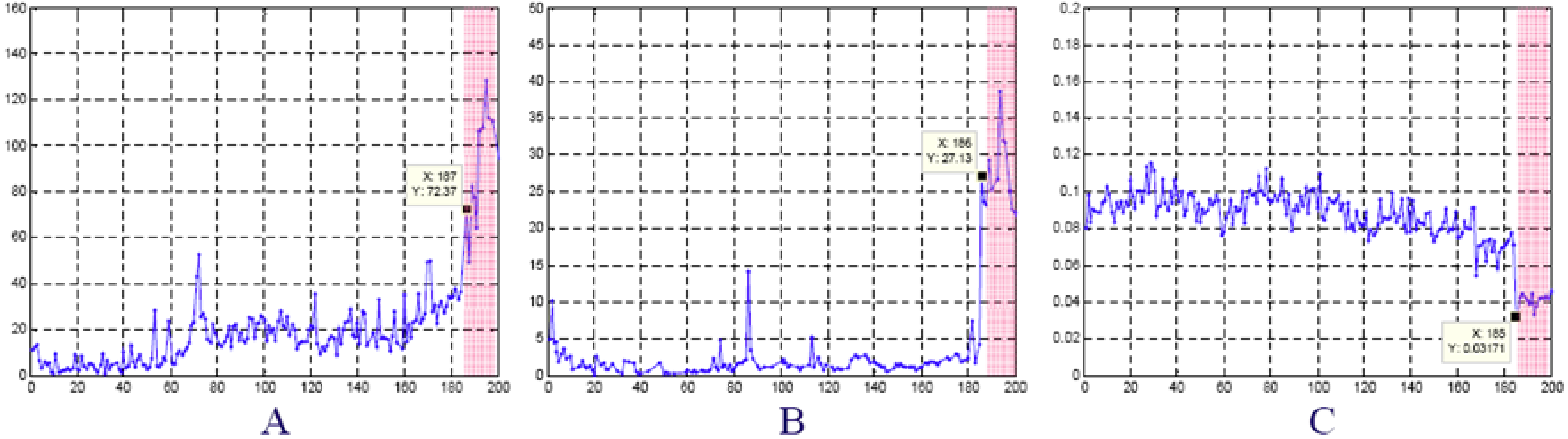
Matlab 기반의 자기 진단 구현

- **Why Matlab Codes for Self-Diagnosis of Vacuum Pumps?**
  - Best choice for linear algebra, such as matrix works (shown so far)
  - Personal attitude of coding ideas: Long history of using matlab in my life

- **7 Stepped Computation Sequences:**
  - Step 1: Reading log files and check 'abnormal and/or crashed' data
  - Step 2: Classifying the idle and gas-loading states using pump motor current signals
  - Step 3: Testing multi-distribution gas-loaded states and separating them
  - Step 4: Estimating APM parameters of NOC batches and stacking them (NOC batch database)
  - Step 5: Extracting distinctive feature vectors from NOC batch matrices using SVD
  - Step 6: Estimating idle and gas-loaded APM parameters for each process
  - Step 7: Projecting the current APM batch vectors to the NOC feature vectors, evaluating and plotting T2 and Q charts.

- **Matlab Code Structure :**
  - Legacy script file: "VP_Diagnosis.m"
  - Live script file: "VP_Diagnosis_live.mlx" → Illustrating its pdf-format file
  - Matlab functions called: svd, mldivide (\), chi2pdf, fpdf, and graphics etc.

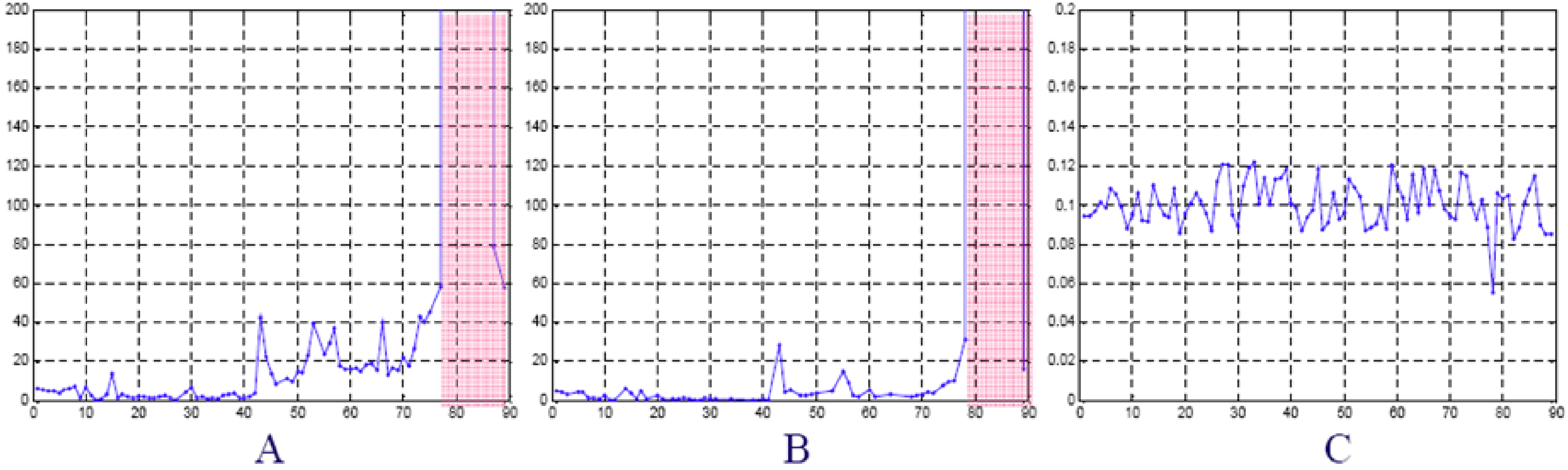
진단 사례 1: 진공펌프 배기성능 (Pumping Speed) 저하



	(A) : T^2 from Gas loaded state batch	(B) : T^2 from Idle state batch	(C) : PSI
Batch NO.	187th	186th	185th

- All diagnostic Model detect the trouble occurrence
- PSI predicts that the pump system will shut down

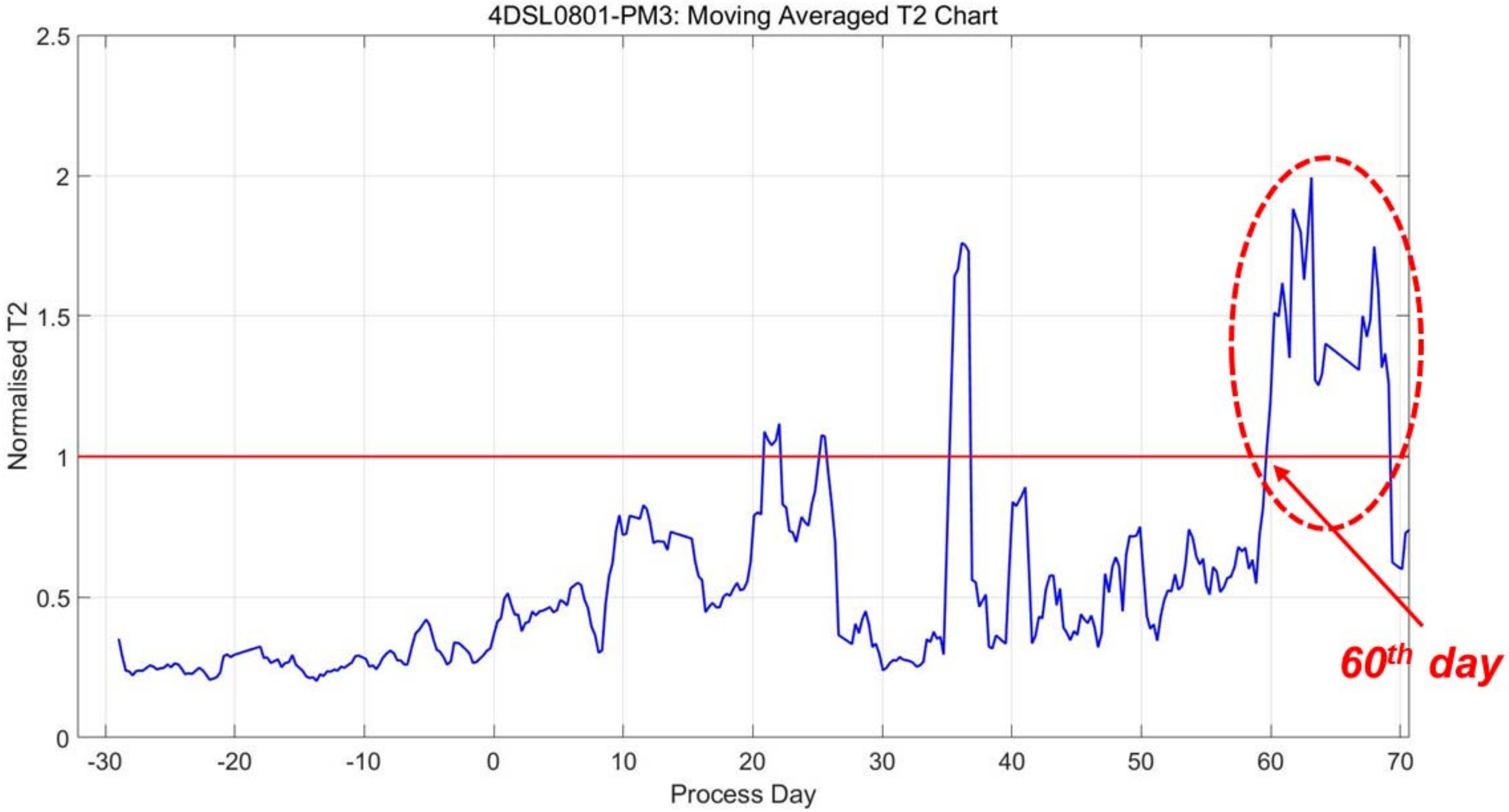
진단 사례 2: BP 모터 과부하 (Overload)



	(A) : T^2 from Gas loaded state batch	(B) : T^2 from Idle state batch	(C) : PSI
Batch NO.	77th	78	X

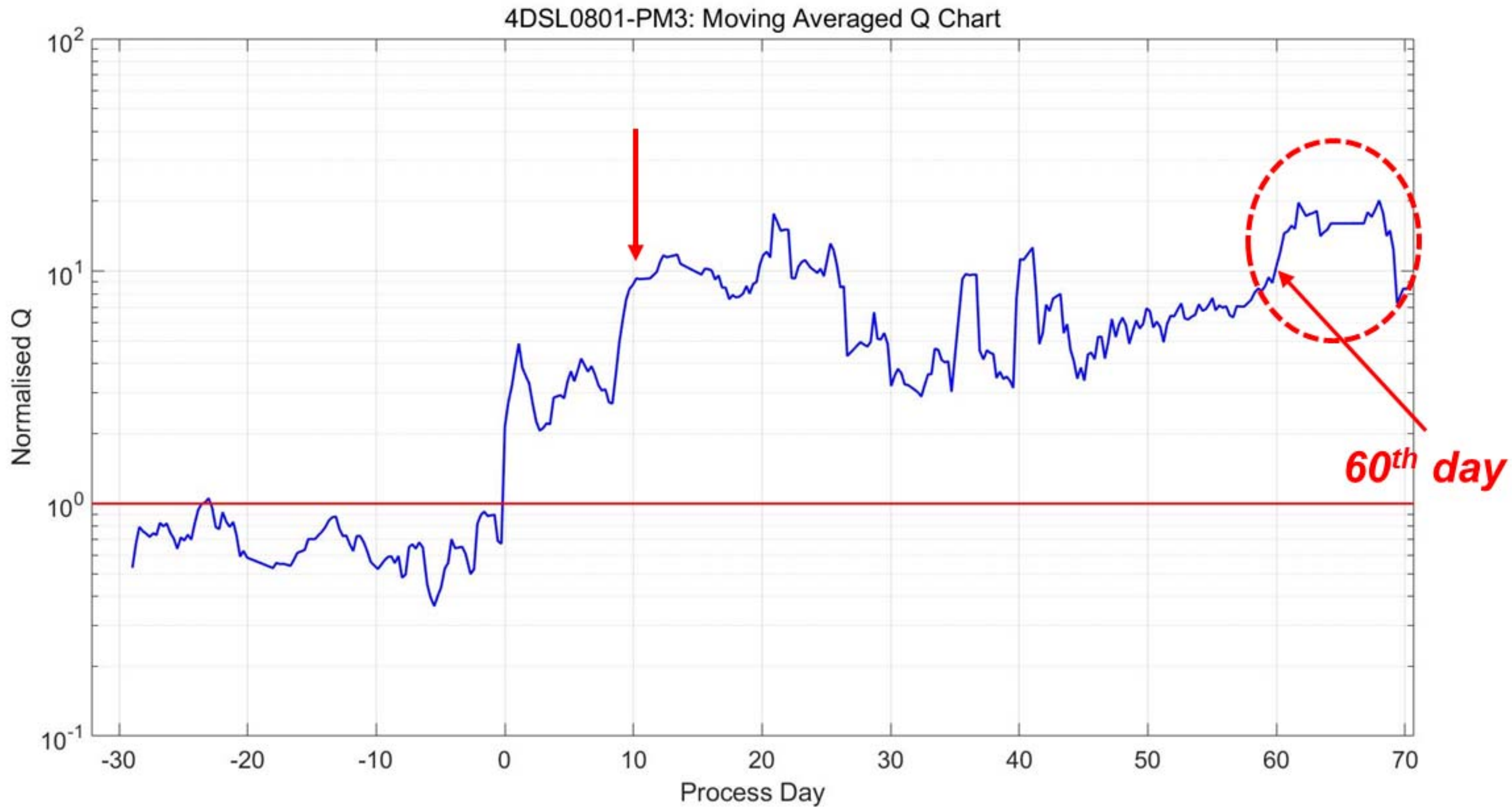
- T^2 detect the trouble occurrence
- PSI can't catch the trouble occurrence

진단 사례 3:



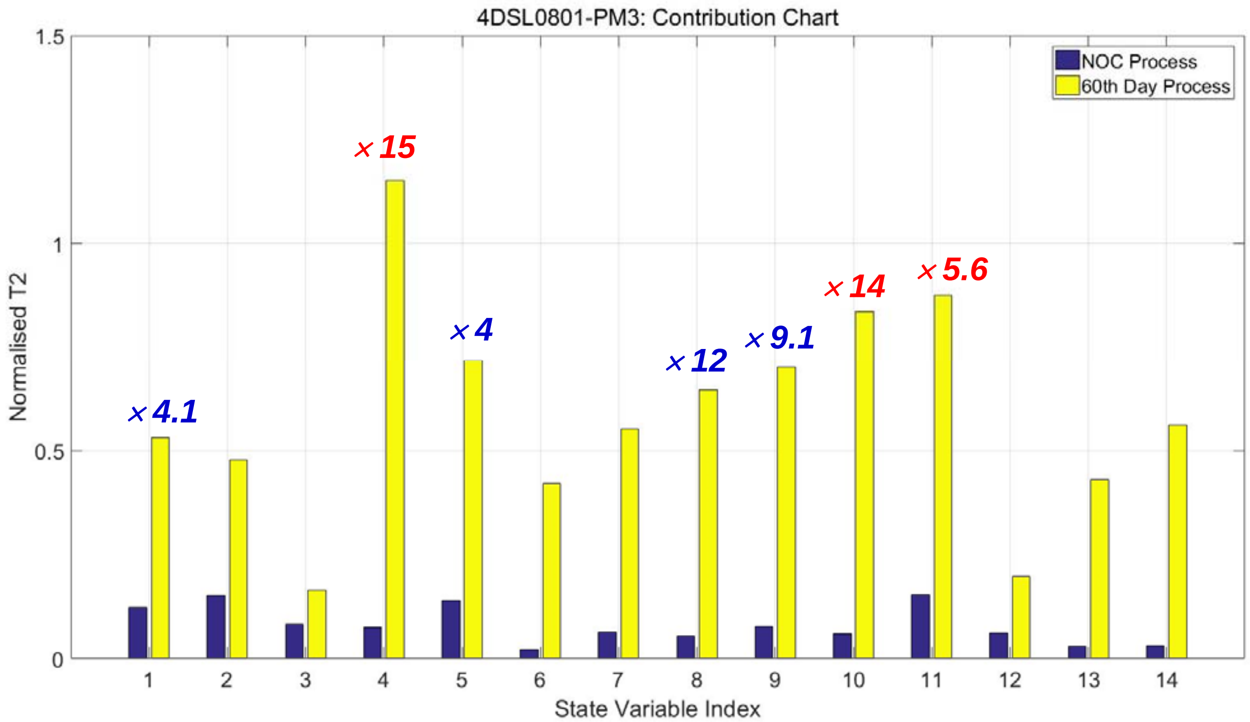
- **Features of 5-Process Moving Averaged T2 Chart:**
  - First 3 peaks: Going back to the normal process states
  - 4th jumped level > 99% C.L. : Stayed in 9 days after 60th day

진단 사례 3:



- **Features of 5-Process Moving Averaged Q Chart:**
  - First 4 peaks: Going back to the process states of Q <=10
  - 4th jumped level > 10×Q-C.L.: Stayed in 9 days after 60th day

진단 사례 3:



- **T2 Contribution Chart:**
  - #1: BP Current, #5: BP Power, #8: DP Current, #9: DP Power
  - #4: BP Inverter Heater Temp, #11: Invert Heater Temp, #10: DP Stator Temp. : Significant state variables MUST be considered for diagnosis

결 론

- 공정현장 Log 데이터 기반의 상태 진단 기술 유효성 검정: 1단계
  - LTO공정 60일째부터 9일 동안 이상 정보 확인: "긍정적 PM 유효성"
    - 20일경과 후 3회 간헐적 경보: 경보 후 정상으로 복귀
  - Matlab Toolbox 혹은 App 기반의 코드 표준화 진행 중

- 공정 현장 적용 및 향후 계획:
  - 세계선도 국내 반도체 및 디스플레이 제조사 진공펌프 운용 실태
    - 반도체(S사, H사): 5 ~ 6만 대의 건식 진공펌프
    - 디스플레이(S사, L사): 2 ~ 3 만 대의 건식 진공펌프
  - 200~300 종의 공정 별 수십 ~ 수백 대의 진공펌프 상태변수 DB 구축 및 실시간 진단:
    - Matlab 기반의 데이터 관리: datastore, timetable, table, tall, etc
    - 병렬 및 분산 처리 채택: 실시간 구현
    - Matlab 전문가 그룹과 긴밀한 협조: AI 및 Machine Learning 등과 융합.