MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN

National Science Foundation

Modeling and Analysis of Cyber-Physical Manufacturing Systems for Anomaly Detection

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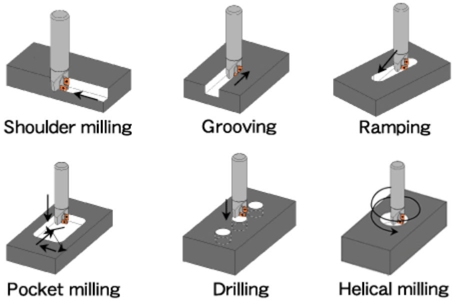
Challenges of anomaly detection

- **Process variability and dynamics:** Combination of transient and steady state operation [1]

- **Part interaction:** Changing loads due to different machine-part interactions



- **Data collection:** Cost and access constraints

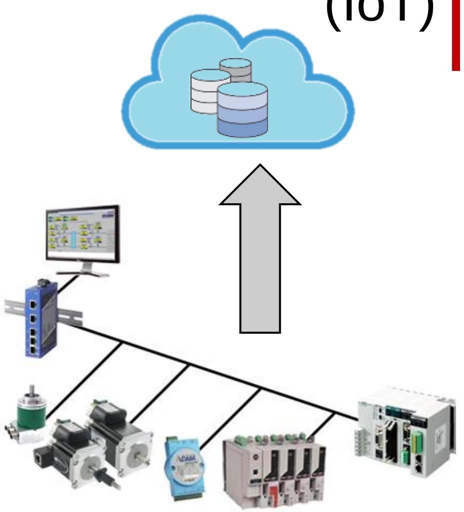
MANUFACTURING PROCESSES ARE COMPLEX

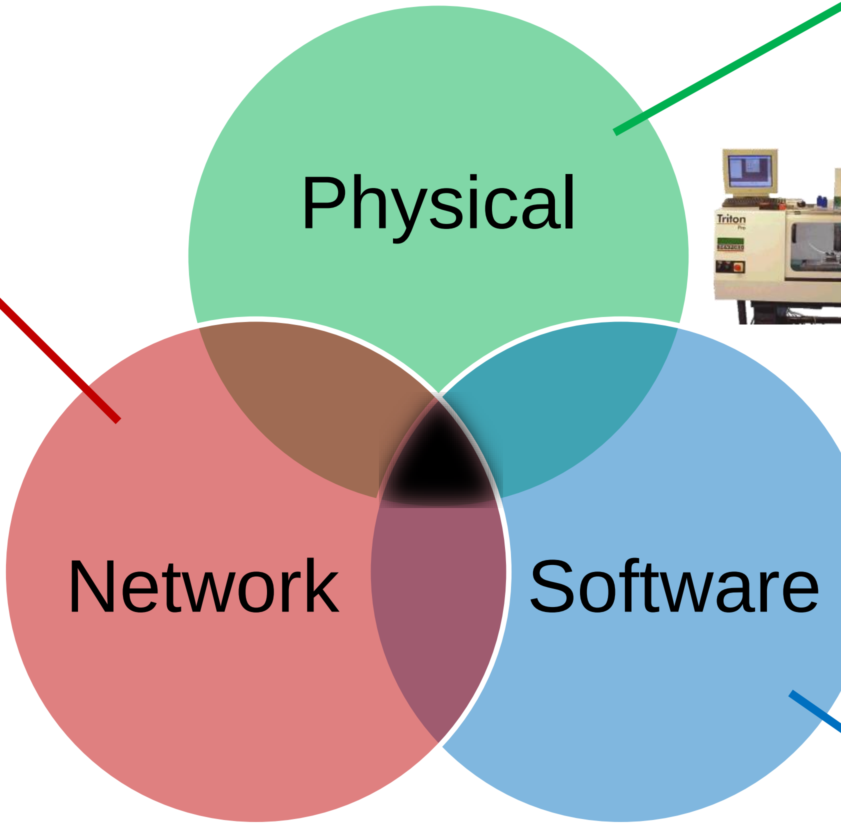
[1] C. Cempel, and M. Tabaszewski. "Multidimensional condition monitoring of machines in non-stationary operation."

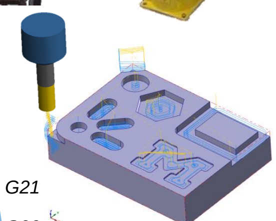
Cyber-Physical Manufacturing Systems

Sensors data [2]
Dynamic models
Part information

DeviceNet
Ethernet/IP
Internet of Things
(IoT)







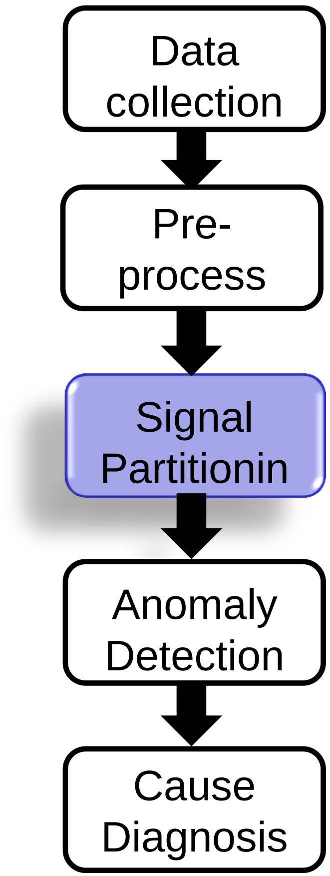
G21
G90
G00 X143.135 Y107.226 S3500
M03
Z60.237
G03 X-.627 Y.627 Z0 I-.627 J0. K0
….

Control logic
Commands
Algorithms

SUPPORT INTEGRATED ANALYSIS OF COMPLEX PROCESSES

Objective

Improve anomaly detection and diagnosis in manufacturing processes



Solution:[3]

- ✓ Model Cyber-Physical Systems considering **both**, **Cyber** and **Physical** domains
- ✓ **Context-specific** analysis of manufacturing operation merging multiple models

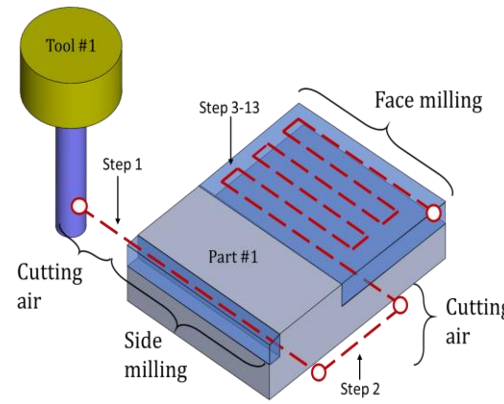
MERGE DATA AND INFORMATION WITH EXPERT KNOWLEDGE

[3] Saez, Miguel, et al. "Anomaly detection and productivity analysis for cyber-physical systems in manufacturing." In *Automation Science and Engineering (CASE), 2017*

Identify Operational Context

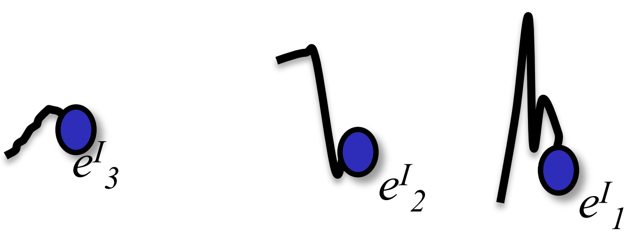
Global Operational State (GOS):

- **Functional:** Reduced controller model
- **Dynamic:** States describing machine dynamics
- **Interactive:** Describe the operations in the part
- **Information:** Explicit process descriptors

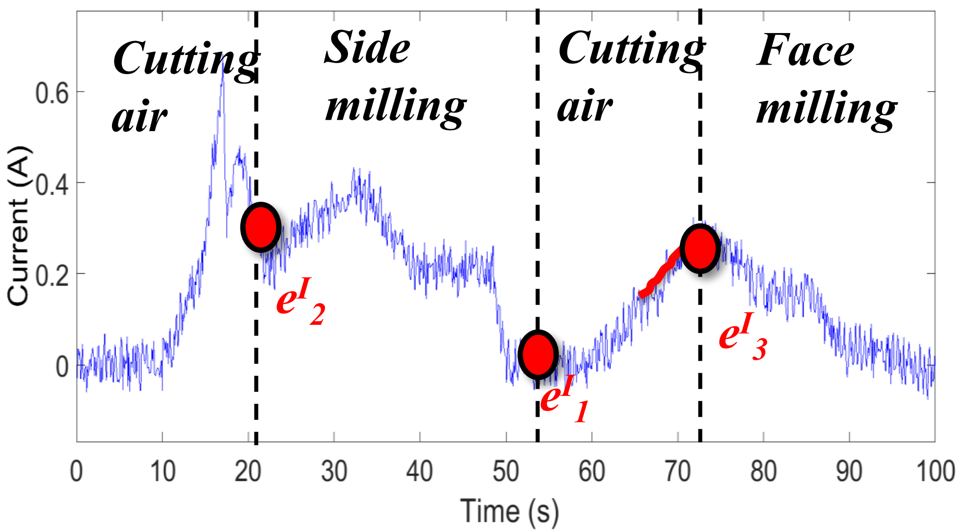


$$G = [Y(1) \dots Y(m)]^T$$

$$e^I = \left[Y_{ref}(1) \dots Y_{ref}(n)\right]^T$$



$\min(DTW(e^I, G))$

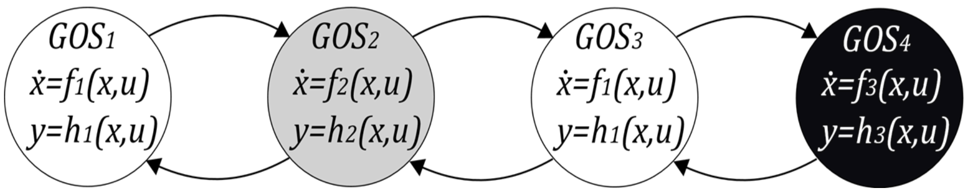


UNDERTAND THE MACHINE OPERATION AND INTERACTION

Define Context-Specific Model

- **Multi-model Specification:**[4]

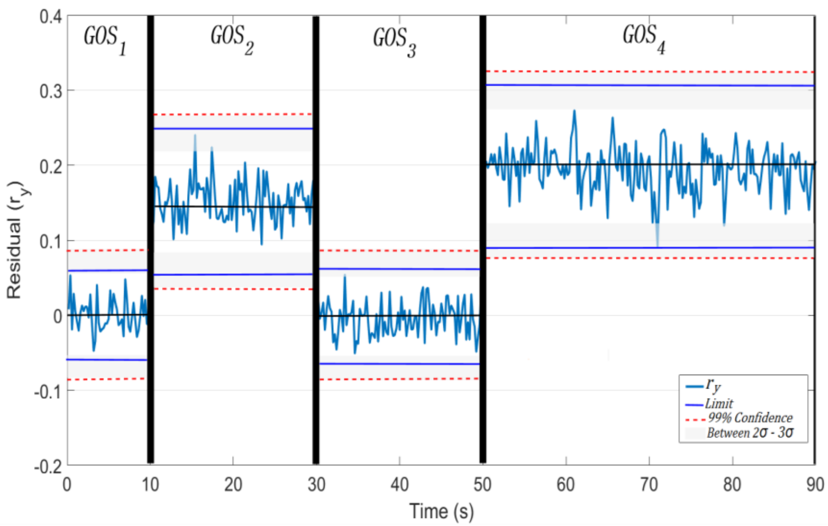
$$M = (GOS, U, X, Y, F, H)$$



GOS: Global Operational State
U: Continuous inputs
X: State variables
Y: Output variables
F: Mapping of state variable functions
H: Mapping of output variable functions

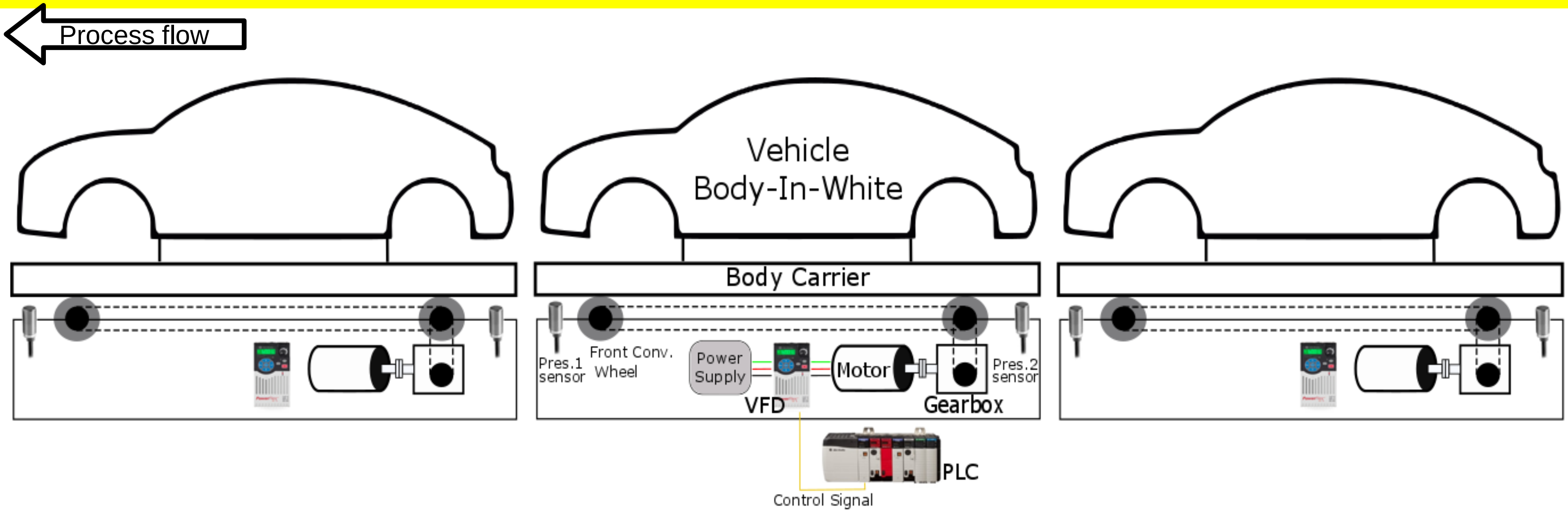
- **Adaptive Threshold Limits:**

$$\Delta r_{GOS} = \mu \pm \psi_R Z\sigma$$



[4] Saez, Miguel, et al. "Context-Sensitive Modeling and Analysis of Cyber-Physical Manufacturing Systems for Anomaly Detection and Diagnosis“, *Transactions in Automation Science and Engineering (TASE), 2018 (Submitted)*

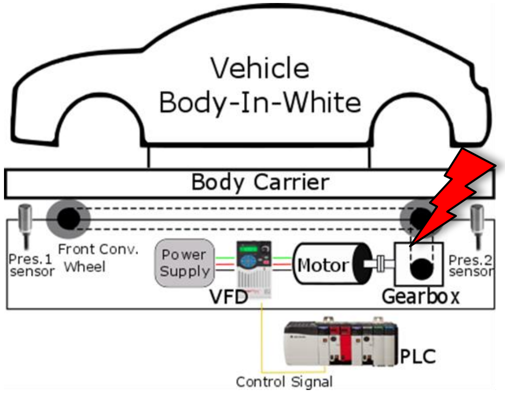
Case Study: Conveyor



- **Available controller data**

Type	Variables
Categorical	Vehicle model
Functional state	Ready, Processing, Down
State-space	Velocity, Torque
Energy	Current, Voltage, Frequency

Case Study: Conveyor



Anomaly detection: Adaptive threshold limits *(Snapshot measurements)*

State	GOS_1	GOS_2	GOS_3	GOS_4	GOS_5
Functional	Proc	Proc	Proc	Proc	Proc
Dynamic	Accel	Accel	Const	Const	Const
Interactive	Part.Out Front/Rear	Part.Out Front	Part.Out Front	Part.In Rear	Part.In Front

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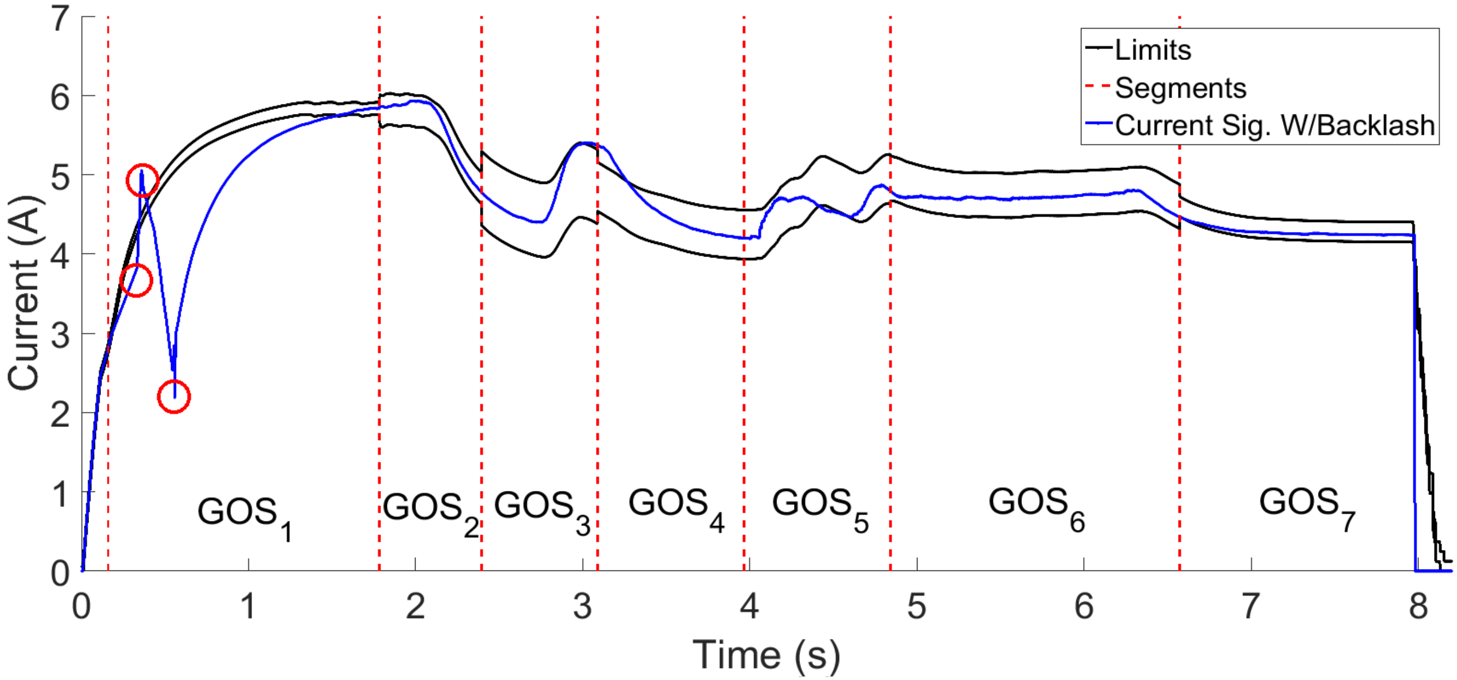
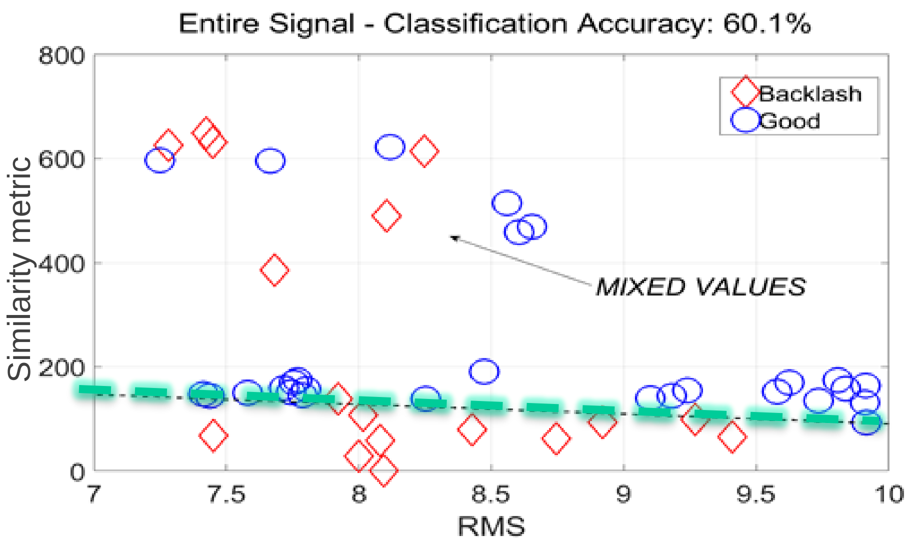
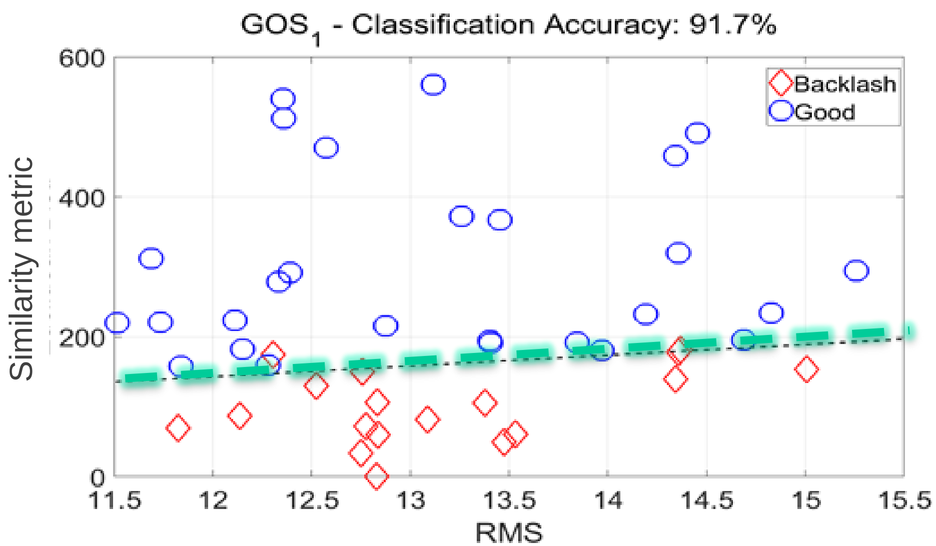


Case Study: Conveyor

Anomaly diagnosis: Supervised learning (SVM) to separate Backlash from Good



Entire signal: 60%



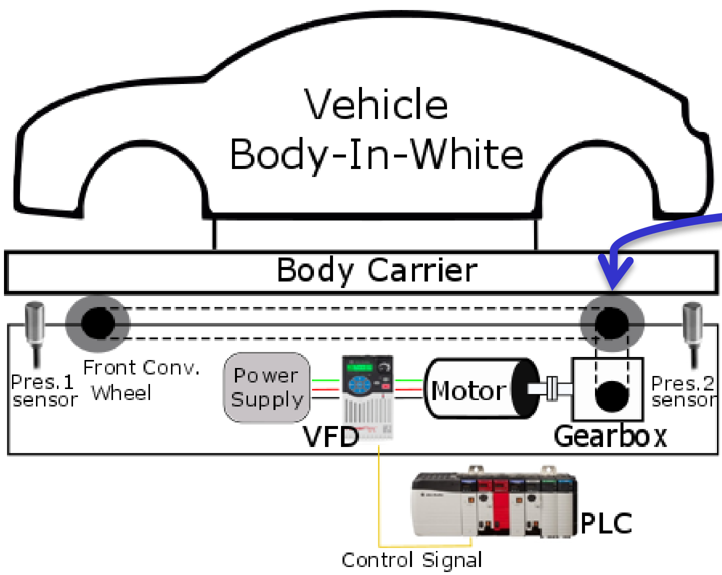
Only GOS_1: 92%

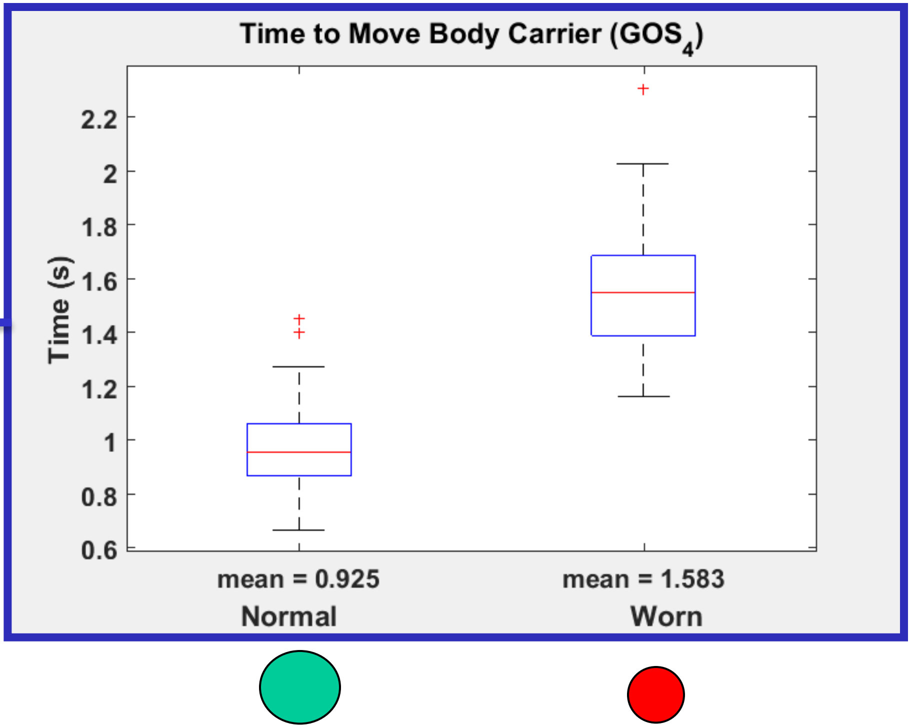
32% IMPROVEMENT IN ROOT CAUSE DIAGNOSIS

Case Study: Conveyor

Productivity analysis: Monitoring time of sub-tasks

Mean increase in time in GOS_4 when wheels are worn



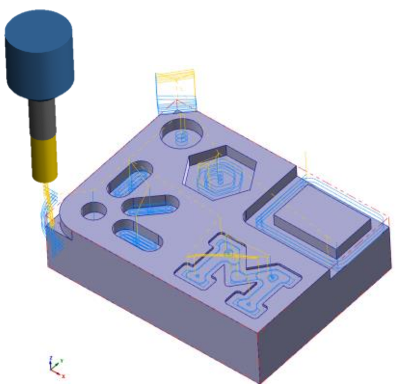


DETECT 0.6 SEC INCREASE IN SUB-TASKS TIME

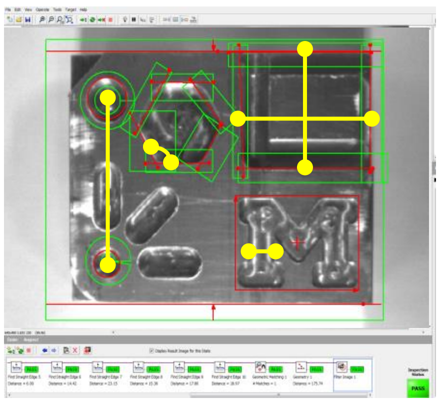
Case Study: CNC Machine

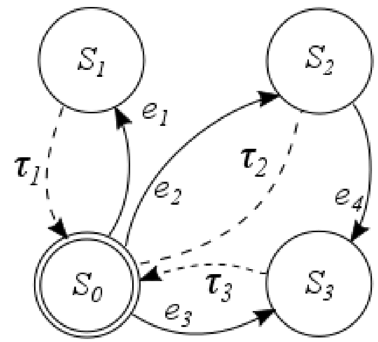
- **Merge sensor data and context information**

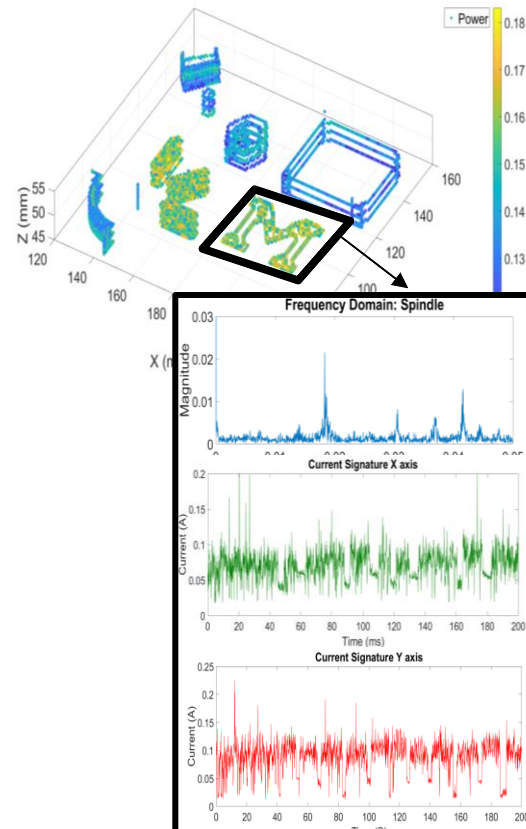
Process step + Artificial vision + Controller model + Energy signature



G21
G90
G00 X143.135 Y107.226 S3500 M03
Z60.237
G03 X-.627 Y.627 Z0 I-.627 J0. K0 .
G00 X155 Y108.54
…

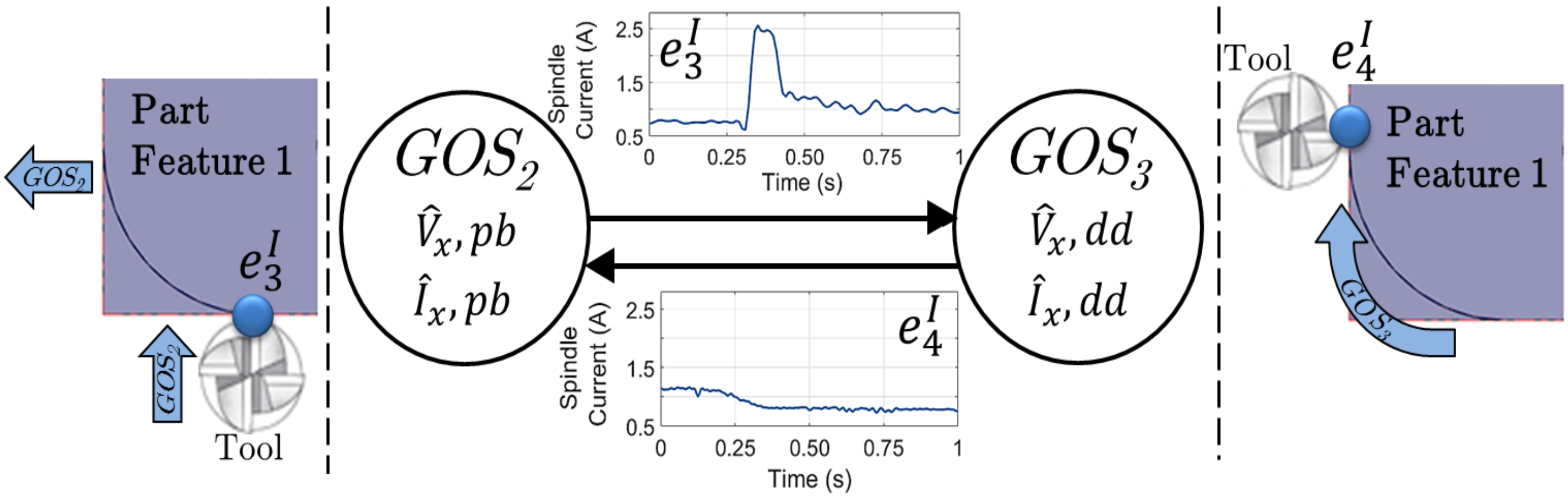






Case Study: CNC Machine

- Multi-Model Framework:



Single Mass dynamic model

$$\hat{I} = Jq + M_{F1}\dot{q} + M_{F0}\sin(\dot{q})/\psi$$

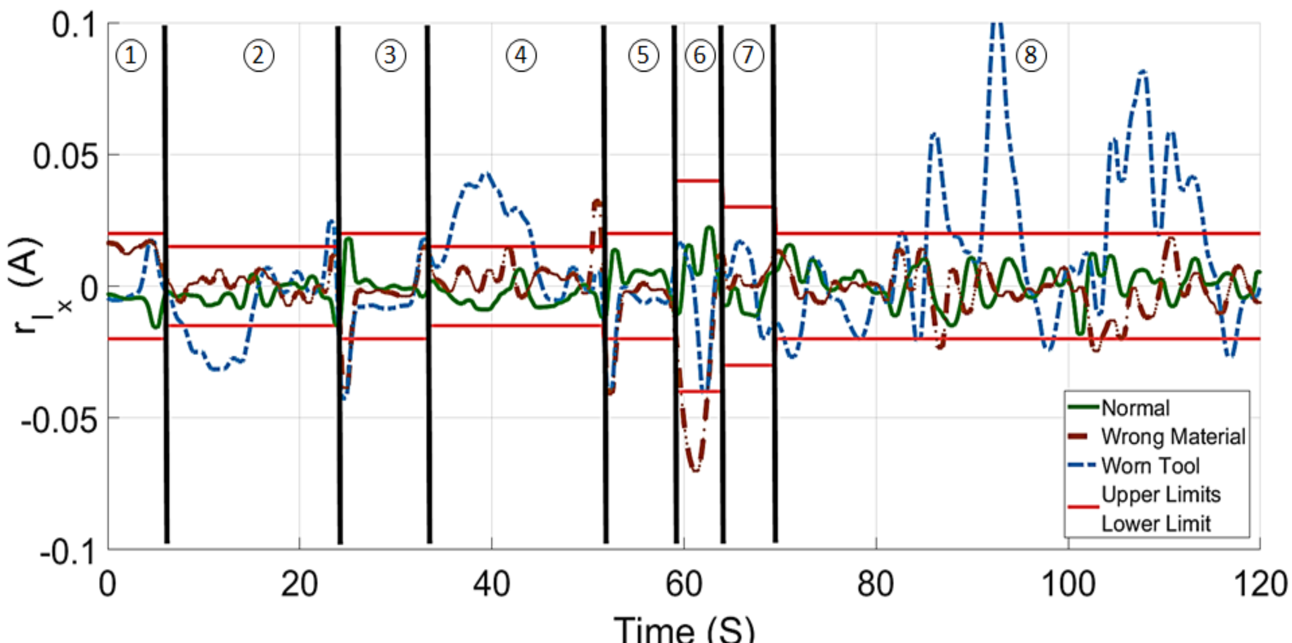
Autoregressive model

$$\phi_I(B)\hat{I} = \phi_{I1}(B)q + \phi_{I2}(B)\ddot{q} + \varepsilon$$

Case Study: CNC Machine

- Multi-Model Framework:

State	GOS 1	GOS 2	GOS 3	GOS 4	GOS 5	GOS 6	GOS 7	GOS 8
Functional	Proc.	Proc.	Proc.	Proc.	Proc.	Proc.	Proc.	Proc.
Dynamic	2 in/sec	5 in/sec	50 in/sec	2 in/sec	2in/sec	2 in/sec	50 in/sec	5 in/sec
Interactive	No Int.	Side Int.	No Int.	Side Int.	No Int.	End Int.	No Int.	Side Int.



DEFINE CONTEXT-SENSITIVE ADAPTIVE THRESHOLD LIMITS

Case Study: CNC Machine

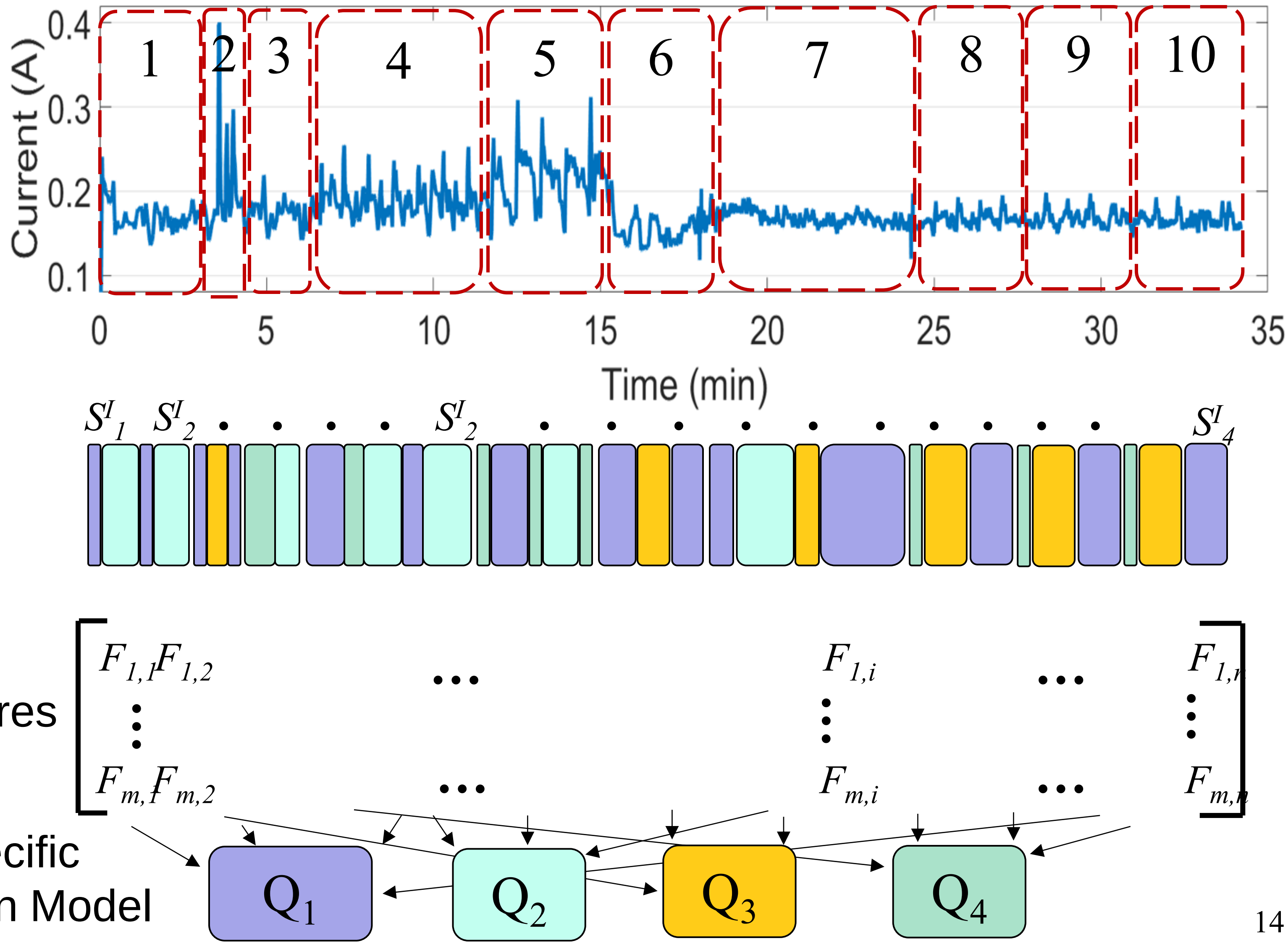
Collect
Raw data

Partition by
part feature

Partition by
Interaction

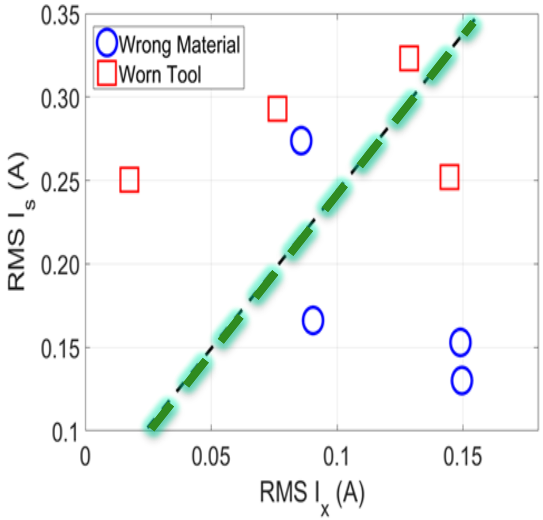
Extract
Signal features

Context-Specific
Classification Model

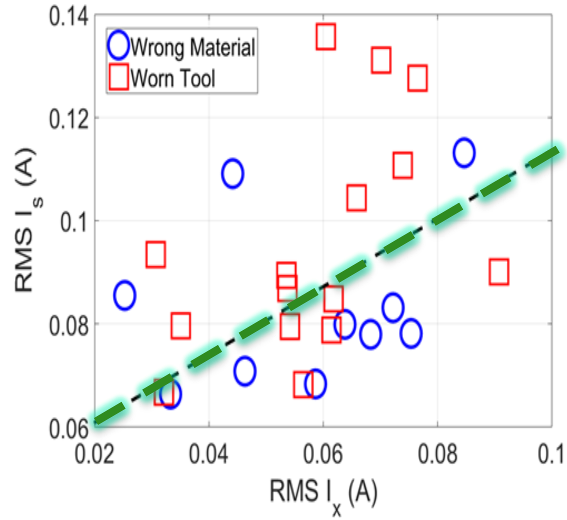


Case Study: CNC Machine

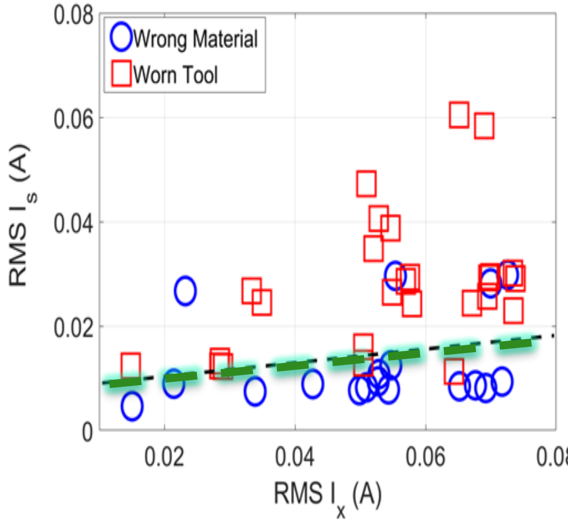
Use supervised learning (SVM) to separate worn tool from wrong material



Entire signal: 75%



Partition by part feature: 81.2%



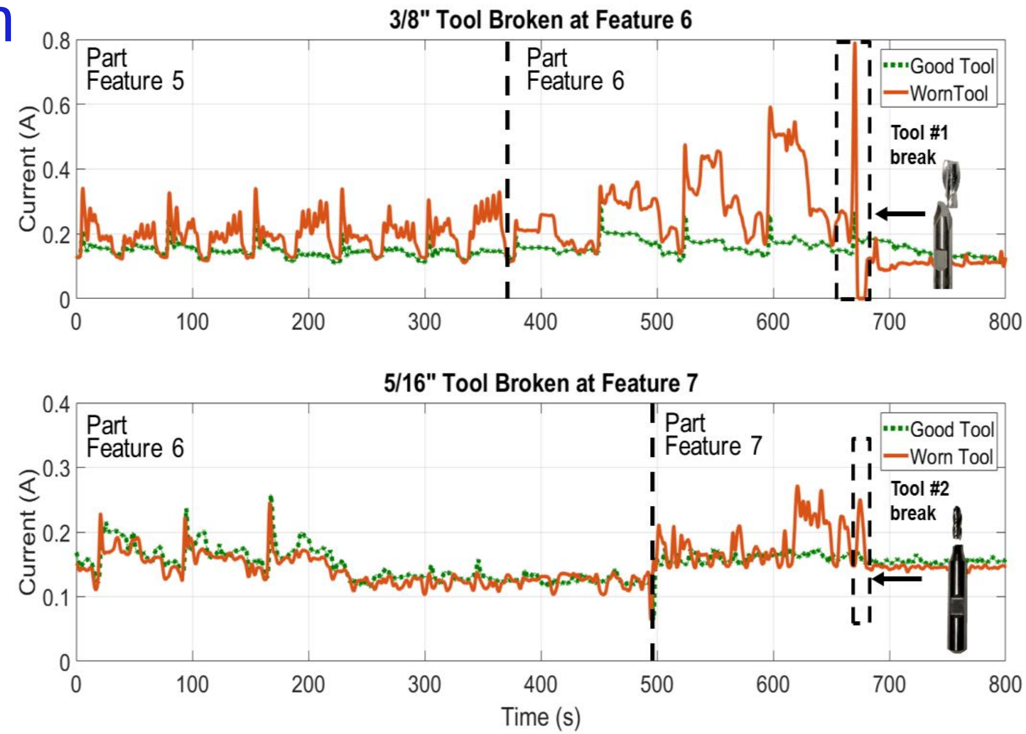
Partition by part feature and GOS: 93.6%

DEFINE CONTEXT-SPECIFIC CLASSICATION MODELS

Case Study: CNC Machine

Develop context-specific diagnosis rules:

- Extract context information
- Identify fault patterns
- Define classification rules



Diagnose tool breakage under different operational context

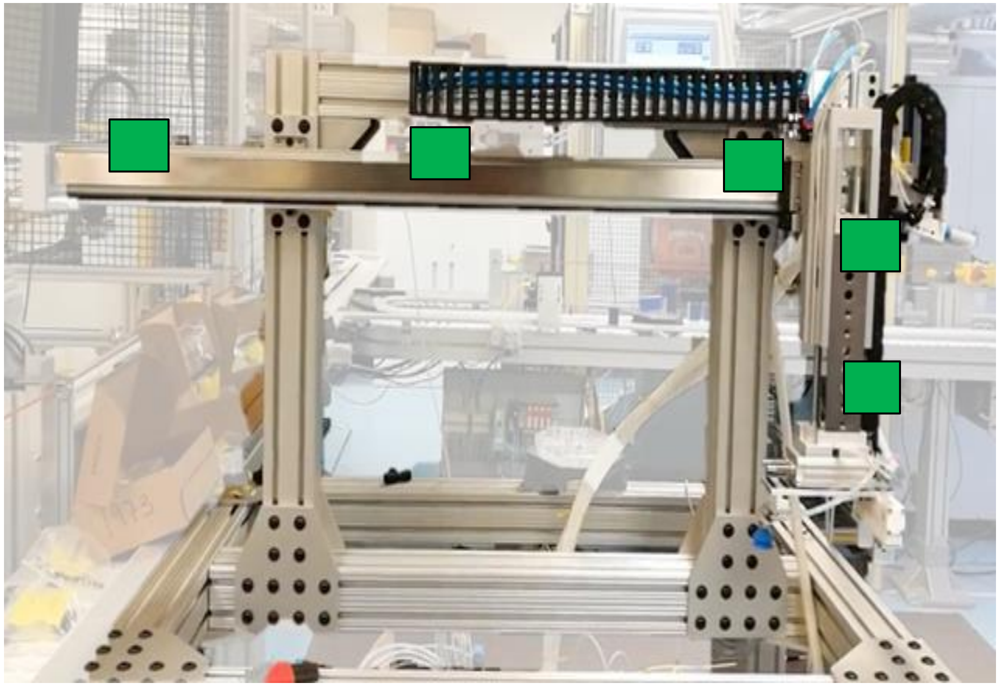
CONTEXT KNOWLEDGE CAN SIMPLIFY DIAGNOSIS

Case Study: Electro-Pneumatic Systems

Common automation applications:

Examples:

- Welding fixtures
- Gantry systems
- Assembly stations

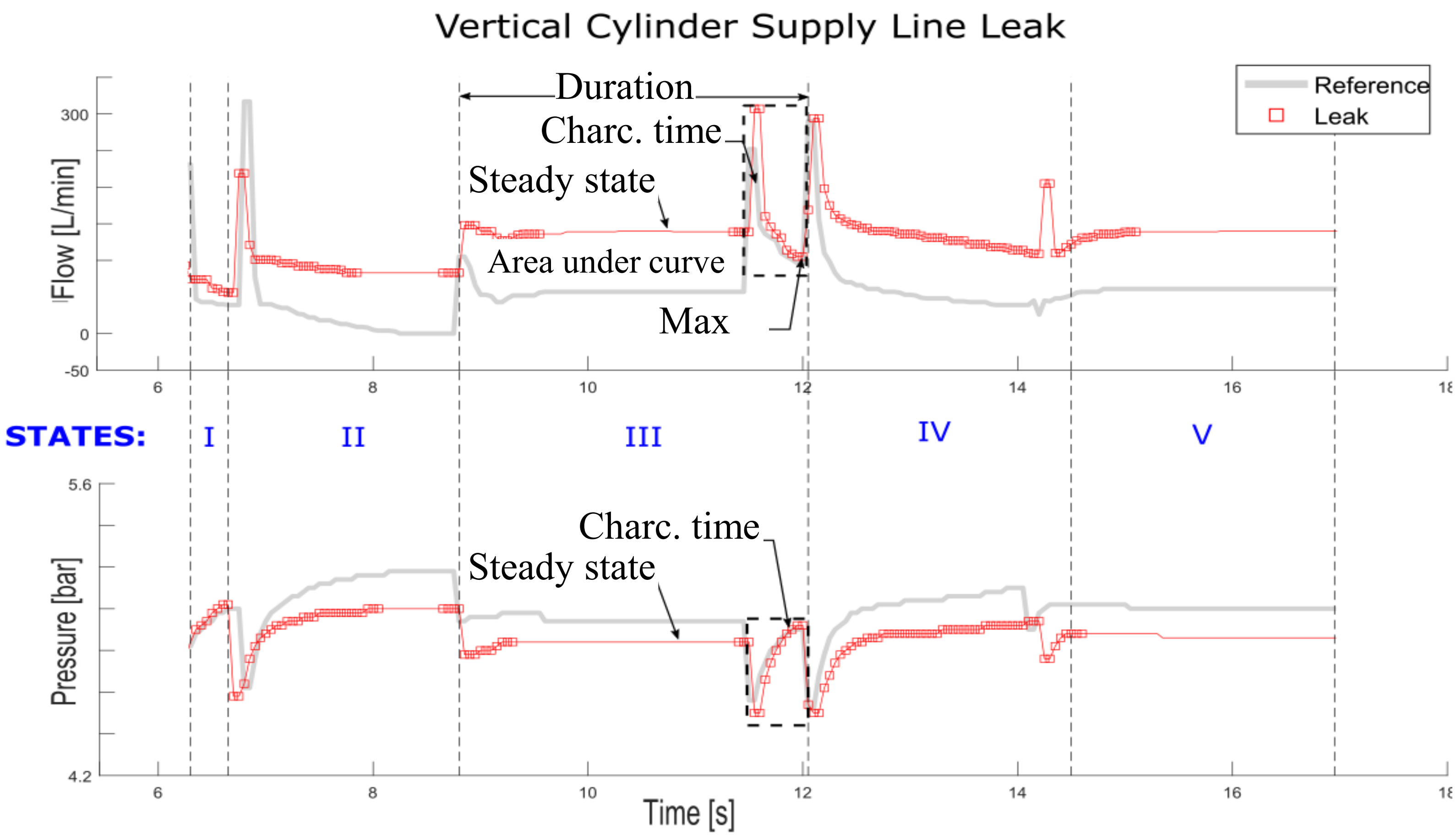


Approach:

- ✓ Monitor data from:
  - Position sensors
  - Pressure and flowmeters
- ✓ Study discrete states

Case Study: Electro-Pneumatic Systems

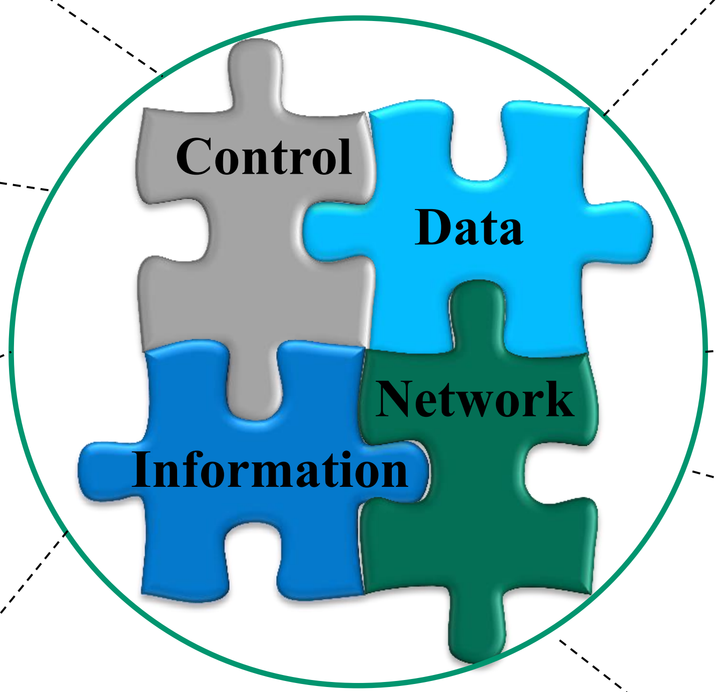
Merge sensor data and controller model to detect leaks in multiple location and sizes



Cyber-Physical Manufacturing Systems

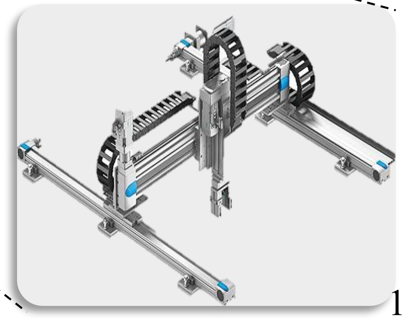
- Worn/Broken tool
- Damaged fixture
- Wrong part

- Worn components
- Backlash



- Joint problems
- Wrong trajectory

- Leaks



Conclusion

- Merging sensor data with context information help to understand the machine operational context
- Feature extraction of a non-stationary signal can be improved by adding information of the cyber domain
- Modeling requires merging expert knowledge and machine data into process analysis algorithms

Thanks