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Exercising Standardization of Prognostics and Health Management (PHM) for Manufacturing Industry

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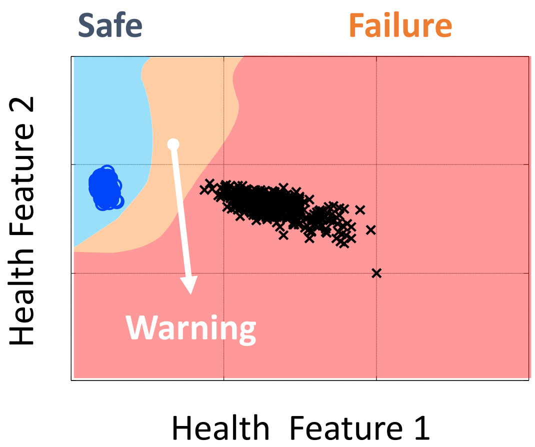
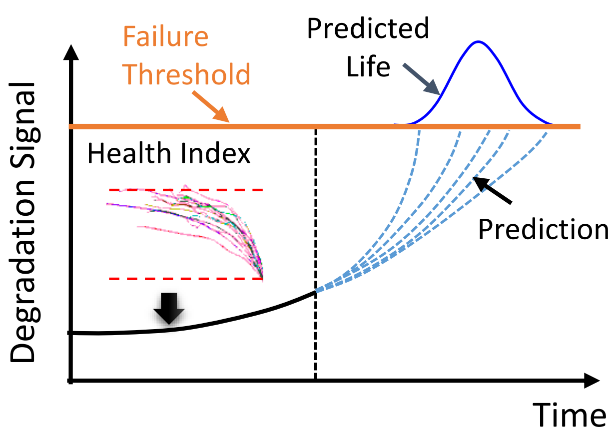
System Health & Risk Management

Importance of Prognostics and Health Management

Prognostics and Health Management





Impacts on Manufacturing Operations

Downtime ↓

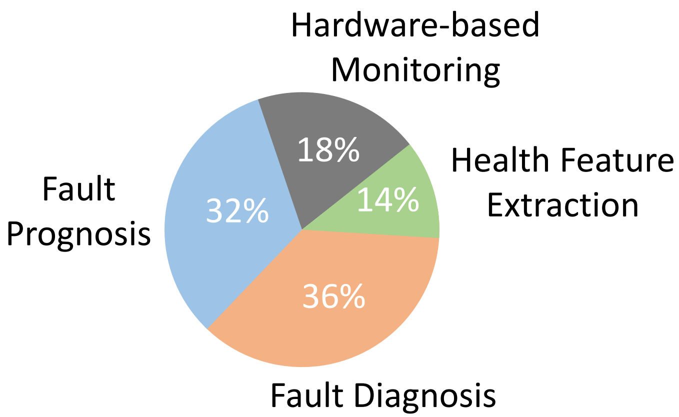
Defective Product ↓

Manufacturing Cost ↓

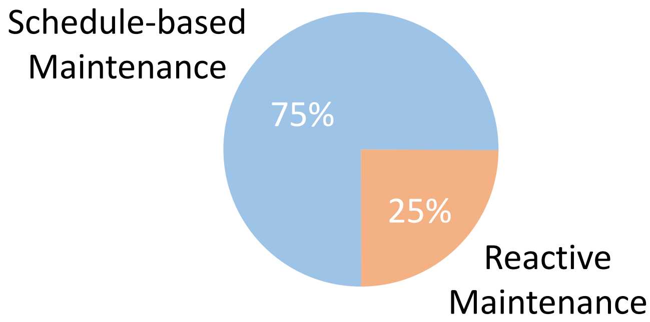
Productivity ↑

Industrial Needs for PHM Standard

Minimum Level of PHM Technologies that Companies Need



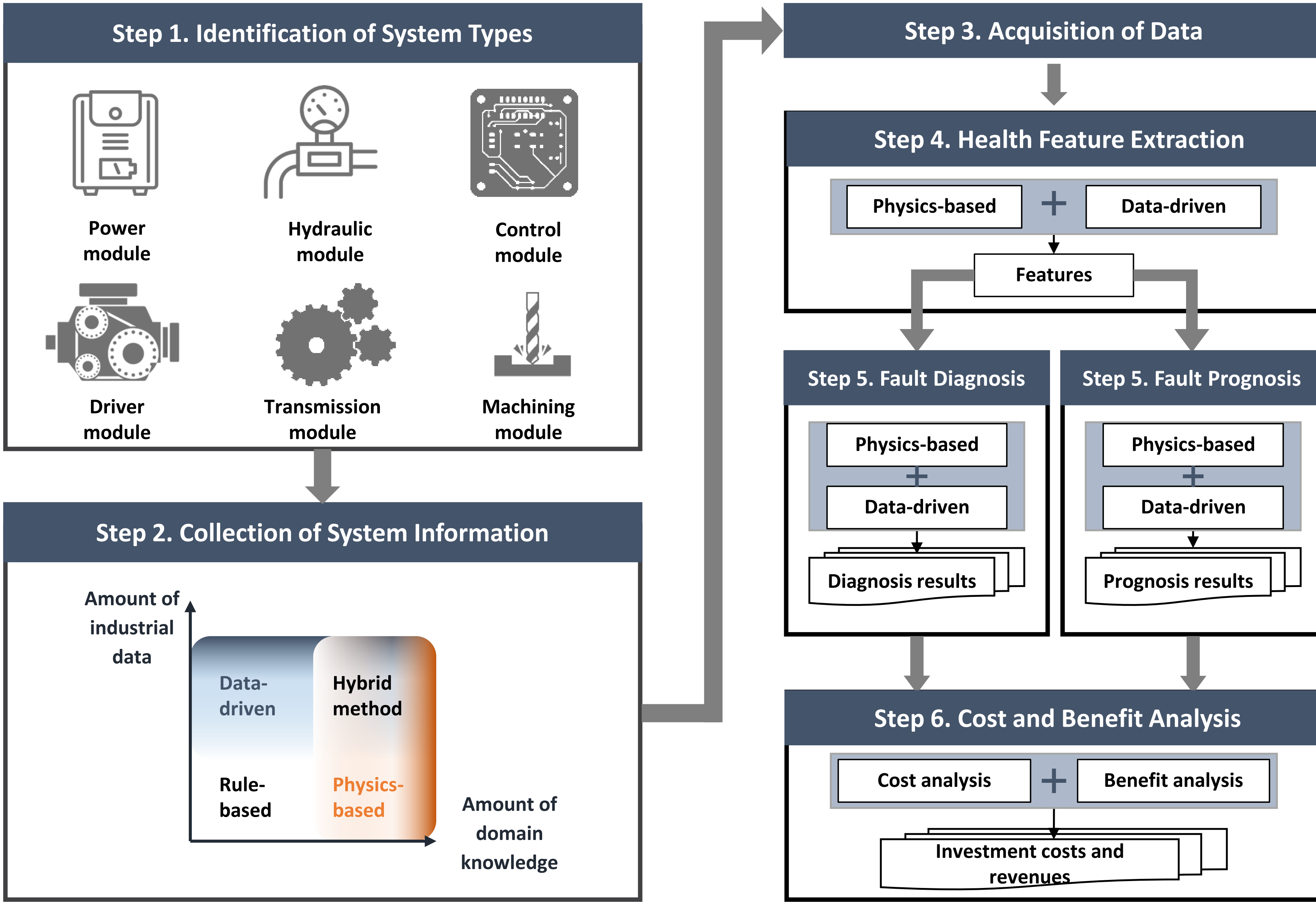
Maintenance Strategies in Companies



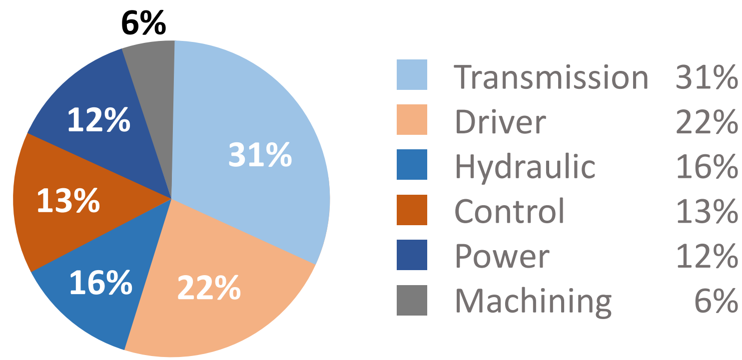
- Technical Advances → Addressed Challenges in PHM
- However, needs for **Standard Framework** for users **without PHM backgrounds**
  - Defines **general process** for PHM development
  - Elaborates **how to choose** PHM approaches **suitable** for a target system

Survey for 41 manufacturing companies in Republic of Korea

Proposed Standard Framework for PHM Development

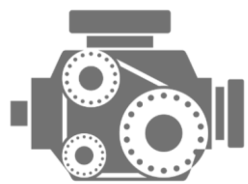


Step 1. Identification of System Types



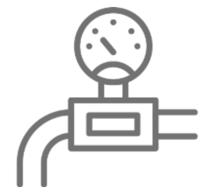
Transmission module

- Reducer
- Ball screw
- Chain & belt
- Gear
- Bearing



Driver module

- Motor
- LM guide
- Hydraulic supply



Hydraulic module

- Cylinder
- Valve

Control module

- PLC
- Inverter
- Switch
- Cable

Power module

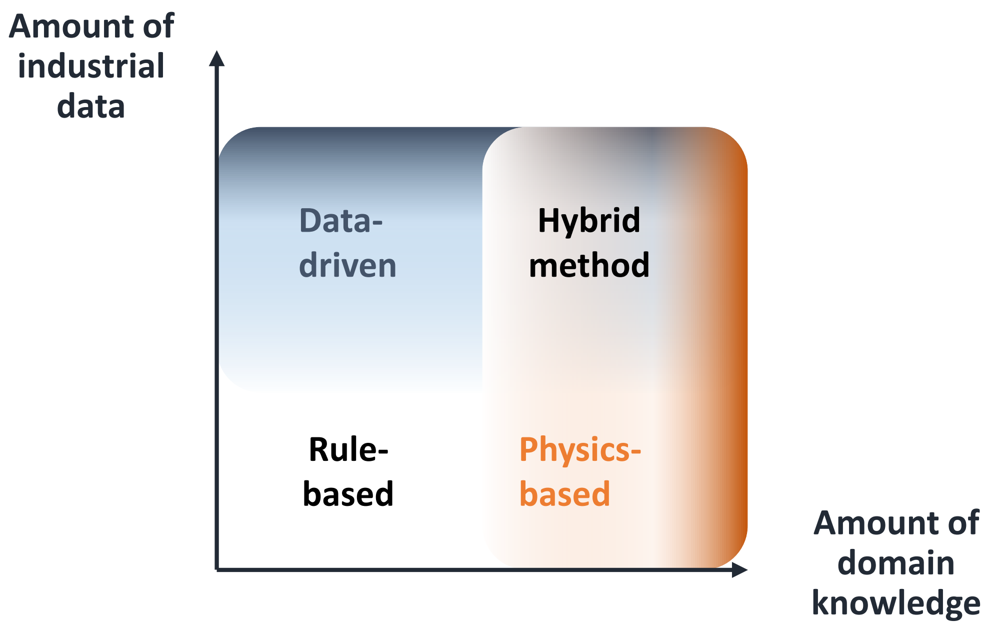
- Power supply
- Transformer
- Battery

Machining module

- Mechanical tool
- Electrical tool

➔ User select a target module/component

Step 2. Collection of System Information



Step 2		Steps 3 to 5
– Large amount of both	→	Hybrid method
– Large amount of industrial data only	→	Data-driven method
– Large amount of domain knowledge only	→	Physics-based method
– Lack of both	→	Rule-based method

➔ User identify amount of information about the target system

Step 3. Acquisition of Data

Module	Component	Vibration	Thermography	Oil Analysis	Process Parameter	Performance	Acoustic Monitoring	Electrical Monitoring
Power module	Power supply	D	P	D	-	-	-	D
	Transformer	D	-	M	-	-	M	M
	Energy storage system	-	M	-	-	-	-	M
Hydraulic module	Cylinder	P	M	M	-	-	P	-
	Valve	D	P	-	D	M	M	-
Control module	PLC	-	-	-	-	-	-	D
	Inverter	-	D	-	-	-	-	D
	Switch	-	-	-	-	-	-	D
	Cable	-	-	-	-	D	D	D
Driver module	Motor	M	M	-	M	M	D	M
	LM Guide	D	-	-	-	-	D	-
	Hydraulic supply	M	M	M	M	M	-	-
Transmission module	Reducer	M	-	M	-	M	D	D
	Ball screw	D	D	-	D	-	-	D
	Chain & Belt	P	-	-	-	-	P	-
	Gear	M	-	M	-	D	D	D
	Bearing	M	M	M	-	-	M	D
Machining module	Mechanical tool	M	-	-	M	M	D	D
	Electrical tool	-	-	-	-	-	-	-

M: Mature and commonly applied in industrial applications*
D: Under development and some initial applications*
P: Promising and potential*

(*: ISO 13379-1: CM and D of machines-Data interpretation and diagnostics techniques)

Step 4. Health Feature Extraction

Module	Component	Failure Mode	Measurement Parameters	Health Feature
Power module	Power supply	Short	Vibration	TDF [1], FDF [1]
	Transformer	Damage in dielectric materials	Gas	DGC [2, 3]
		Partial discharge	Partial discharge	FDF [4, 5]
		Mechanical damage	Impedance	R, L, C [6, 7]
			Vibration	TDF, FDF [8-11]
	Energy storage system	Short	Impedance	R, L, C [12]
			Voltage	TDF [13]
Hydraulic module	Cylinder	Abrasion	Vibration	TDF [14]
			Oil	empirical parameters [15]
			Temperature	TDF [16]
			Resistance	TDF [16]
	Valve	Abrasion	Vibration	entropy [17], SF [18], empirical parameters [19, 20]
			AE	TDF [21]
			Sound	SF [18]
			Pressure	PV Diagram [22]
			Velocity	TDF [23]
Control module	PLC	Malfunction	-	-
	Inverter	Short	Voltage	TDF [24, 25]
	Switch	Short	Voltage	TFDF [26]
	Cable	Short	Gas	TDF [27]
			Mechanical properties	hardness [27, 28]
			Voltage	TDF [29], FDF [28, 29]
			Impedance	R, L, C [28, 29]
Driver module	Motor	Short	Current	FDF [30, 31], profile [32], TDF [33]
			Voltage	TDF [33], FDF [34], phase [35], residual error [36]
			Electric power	FDF [34, 37]
			Torque	Profile [35], FDF [38]
			Magnetic flux	FDF [39, 40]
			Vibration	FDF [41]
			Impedance	TDF [36]
			Temperature	TDF [42]

Module	Component	Failure Mode	Measurement Parameters	Health Feature
Driver module	LM Guide	Abrasion	Vibration	FDF [43, 44]
			AE	FDF [44]
	Hydraulic supply	Leakage	Temperature	TDF [45-47]
			Viscosity	TDF [45]
			Vibration	TDF [47], FDF [46]
			Flow rate	TDF [48]
			Pollution level	TDF [45]
Transmission module	Reducer	Abrasion	Vibration	SF [49], FDF [50-54],
			Magnetic field	TDF [55]
			Sound	TDF [56]
			AE	energy [57]
			Electric power	TDF [58]
	Ball screw	Abrasion	Vibration	FDF [59], backlash [60]
			Current	empirical parameters [61]
			Velocity	empirical parameters [61]
	Chain & Belt	Short	Vibration	TDF, FDF
	Gear	Abrasion	Vibration	empirical parameters [62], TFDF [63], energy [63-65]
			Magnetic field	TDF [55]
			Sound	TFDF [64]
			AE	TDF [66], energy [57]
	Bearing	Abrasion	Vibration	TDF [67-71], FDF [72, 73]
			AE	TDF [74, 75]
			Sound	energy [68, 76, 77]
			Current	TDF [78], FDF [79], TFDF [80]
			Frequency	FDF [81]
			Magnetic field	TDF [82]
Machining module	Mechanical tool	Abrasion/deformation	Mechanical force	empirical parameters [83, 84], TDF [85-88]
			Vibration	TDF [87], FDF [88, 89]
			Current	TDF [90]
			Surface roughness	RMS [91, 92]
			AE	TDF [93, 94], FDF [93, 94]
			Voltage	TDF [88]
	Electrical tool	Abrasion/deformation	Vibration	TDF, FDF

Step 5. Fault Diagnosis

Module	Component	Failure Mode	Fault Diagnosis	
			Physics-based/Rule-based	Data-driven
Power module	Power supply	Short	-	Back propagation NN [95], Random forest [96]
	Transformer	Damage in dielectric materials	Fuzzy logic [97][98][101], Association rule-mining (ARM) classifier [105]	k-NN [99] Back propagation NN [99] ANN [101] Multi-layer SVM [100][101] Gene expression programming (GEP) [101]
		Partial discharge		
		Mechanical damage		
	Energy storage system	Short	Discrete event system model [102], Residual generation by Kalman filter (KF) [103], Extended Kalman filter (EKF) [104], Thermal modeling [105]	Functional SVM [106], Correlation assessment [107]
Hydraulic module	Cylinder	Abrasion	Thermodynamic process modeling [108]	RBF kernel SVM [109], k-NN [109], Back propagation NN [109][110], ANN [111][112], Genetic NN [112]
	Valve	Abrasion	-	Probabilistic NN [113], NN ensemble [114], ANN [115]
Control module	PLC	Malfunction	Petri-net [116], State transition diagram [117]	Bayesian network [118]
	Inverter	Short	Fuzzy logic[119] Residual generation by mixed logical dynamic (MLD) model[120] Current residual vector[121]	Multilayer perceptron network [122] Genetic NN [123]
	Switch	Short	Residual generation by extended Kalman filter (EKF) [124] Sensor fault model [125]	Back propagation NN[126] Elman NN [126] Fuzzy c-means (FCM) [126]
	Cable	Short	Electric arc model [127], High-impedance fault model [128]	Self-organizing map algorithm [129]
Driver module	Motor	Short	Stator and rotor faulty model [130] Swing-angle model [131]	Hebbian-based unsupervised NN [132] RBF kernel SVM [133]
	LM Guide	Abrasion	Linear rotor bearing kinematic model [134], High frequency resonance technique (HFRT) [135][136]	-
	Hydraulic supply	Leakage	Frequency response diagram (FRD) [137][138]	Multilayer back propagation NN [139]
Transmission module	Reducer	Abrasion	-	Transductive SVM [140]
	Ball screw	Abrasion	Residual generation by Kalman filter (KF) [141]	Self-organizing map algorithm [142] Coefficient of variation [143]
	Chain & Belt	Short		Kernel SVM [144], ANN [144] Self-adaptive growing NN [145]
	Gear	Abrasion	Residual generation by autoregressive (AR) filter [146]	Wavelet SVM [147], Multimodal deep support vector classification [148], Proximal SVM [149], ANN [149][150], c5.0 [149]
	Bearing	Abrasion	-	Kernel SVM [151], Wavelet SVM [152], One-classv-SVM [153], ANN [151], Fuzzy lattice classifier [154], Decision tree [154]
Machining module	Mechanical tool	Abrasion/deformation	Mechanistic force model [155]	Hidden Markov model (HMM) [156]
	Electrical tool	Abrasion/deformation	If then rule [157]	Recurrent NN [158]

Step 5. Fault Prognosis

Module	Component	Failure Mode	Fault Prognosis	
			Physics-based/Rule-based	Data-driven
Power module	Power supply	Short	Equivalent series resistance process modeling [159], Physics-based component aging models [160], Particle Filter [161]	Simple state-based method [162], Gaussian Process Regression [163]
	Transformer	Damage in dielectric materials	Perks' Hazard Function [164], Population prediction model [165], Bayesian Particle Filter [166]	Logistic Regression [167]
		Partial discharge		
		Mechanical damage		
	Energy storage system	Short	Extended Kalman Filter [168][169], Particle Filter [170][171][172]	Gaussian Process Regression [173]
Hydraulic module	Cylinder	Abrasion	-	Kernel Regression [174]
	Valve	Abrasion	Particle Filter [175][176], Kalman Filter [177], Valve fluid flow mode [178], Gamma process model [179]	Neural Network [180]
Control module	PLC	Malfunction	-	-
	Inverter	Short	Particle Filter [161]	Gaussian Process Regression [163], Weibull General Renewal Process [181]
	Switch	Short	Particle Filter[161], Crow-AMSAA model[182]	Gaussian Process Regression [163]
	Cable	Short	General Path model [183]	A Sliding-window Regression [184], Support Vector Regression [185]
Driver module	Motor	Short	Particle Filter [186]	Hidden Markov Model [187][188], Recursive Least Square [189], Neural Network [190]
	LM Guide	Abrasion	-	-
	Hydraulic supply	Leakage	Kalman Filter [191]	-
Transmission module	Reducer	Abrasion	-	-
	Ball screw	Abrasion	-	-
	Chain & Belt	Short	-	-
	Gear	Abrasion	Particle Filter [192], Fast crack propagation model [193], Linear Kalman Filter[194], Paris Law [195]	Back Propagation Neural Network [196], Hidden Markov Model [197]
	Bearing	Abrasion	Kalman Filter [198][199], Particle Filter [200][201], Paris Model [202][203], LP&IH Model [204]	Neural Network [205][206][207][208], Support Vector Regression [209][210][211][212], Recursive Least Square [213], Gaussian Process Regression [214], Hidden Markov Model [215]
Machining module	Mechanical tool	Abrasion/deformation	Saucer's local linear model [216]	Continuous Hidden Markov Model [217], Mixture of Gaussian Hidden Markov Model [218], Neural Network [219][220], Support Vector Regression [221][222], Bayesian random sample path approach [223]
	Electrical tool	Abrasion/deformation	-	-

Step 6. Cost and Benefit Analysis

Conduct Asset Degrader Analysis	Cost of PHM Technology Development & Implementation	The Benefits of the Technology Implementation	Calculate Decision Metrics
• **Select critical asset for mission or objective** (Machine tools, Inflight tanker) • **Select top degraders of asset** (based on reliability & availability by interview)	• **Perform FMECA to design architecture of the PHM system** (sensor, quantity, location) • **Development** a. *Algorithm Development* b. *Hardware and Software* c. *Qualification & Testing* d. *System Integration* e. *Integrated data environment* • **Implementation** a. *Manufacture PHM sensor* b. *Installation*	• **A literature search** • **Brainstorming sessions with colleagues and other PHM practitioners for determining benefits** • **Interviews with operators and maintainers** • **Etc.**	• **“ Is it worthy? ”** • **Return on Investment(ROI)** $= \frac{Benefit - Cost}{Cost}$ • **Payback** $= \frac{Cost}{Monthly\ Benefit}$ • **Net Cash Flow etc**

“How Engineers Can Conduct Cost-Benefit Analysis for PHM Systems”, Jeffrey Banks (2009)

Summary

- 6-step standard framework for PHM development
- Six fragile modules for manufacturing industry
- Reference tables to help to choose PHM approaches suitable for each target system

6-step processes for PHM development	**Reference Table**
Step 1: Identification of System Type	6 Types of System
Step 2: Collection of System Information	4 Different Approaches
Step 3: Data Acquisition	7 Types of Data
Step 4: Health Feature Extraction	Health Features
Step 5: Fault Diagnosis/Prognosis	Diagnostic/Prognostic Methods
Step 6: Cost and Benefit Analysis	

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THANK YOU FOR LISTENING