NSF I/UCRC since 2001

# Recent Advances and Transformation Direction of *PHM*


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Intelligent Cyber Machine Systems
Univ. of Cincinnati, Univ. of Michigan, Missouri Univ, of S&T, Univ. of Texas-Austin






## Outline

- Evolution of Manufacturing and PHM
- Changing Big Data Environment and Emerging Technologies on Big Data Analytics, Cyber-Physical Systems, and Industry 4.0
- Lessons Learned from PHM and New Applications
- Conclusions

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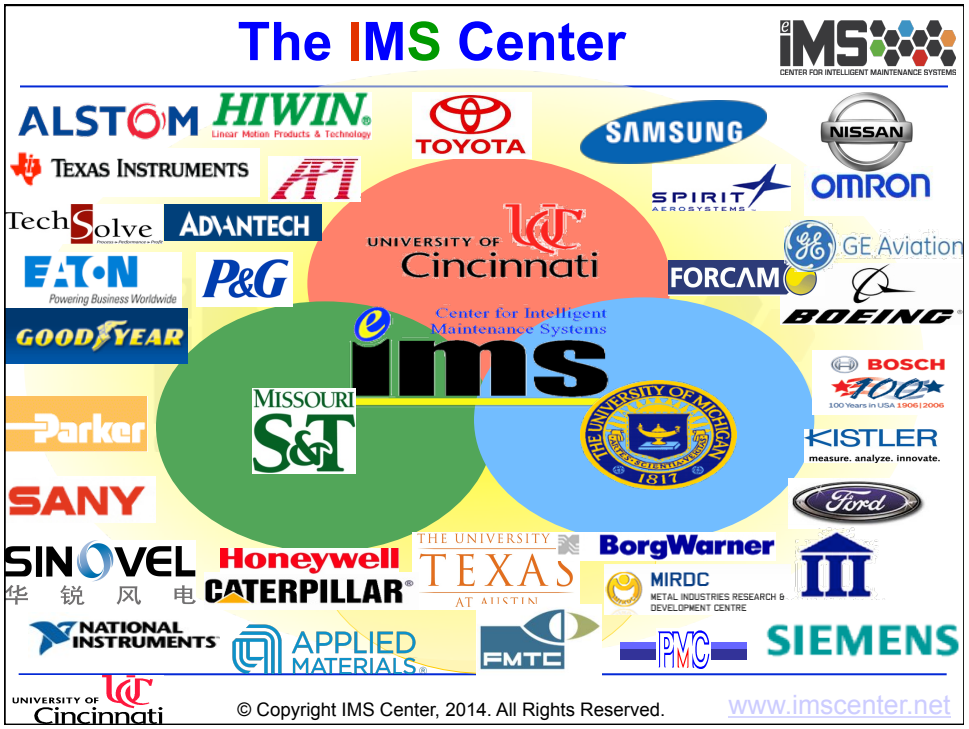
# The IMS Center



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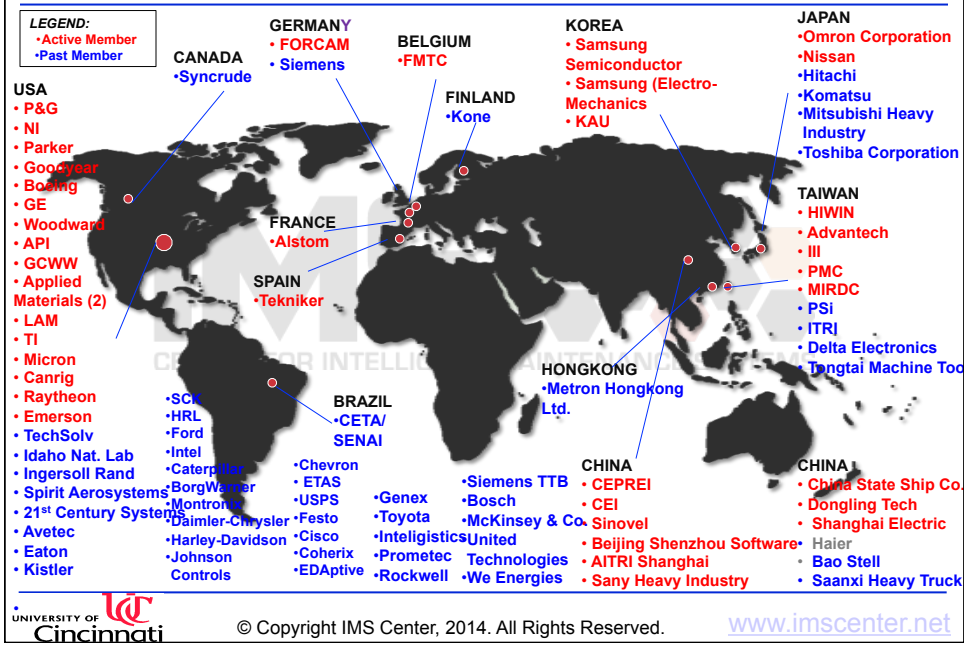
# Global Industry Partners (80+)



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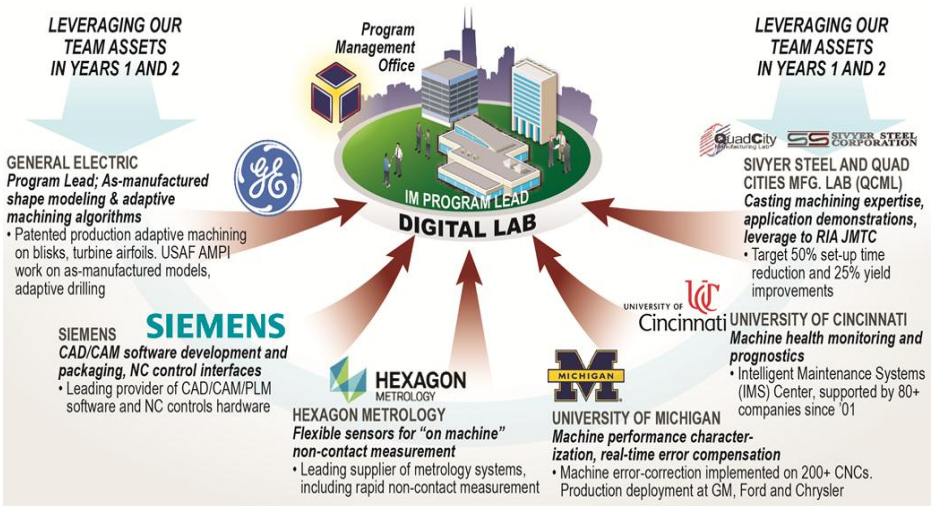
## White House Digital Manufacturing and Design Innovation (DMDI) —Led by UI Lab (Feb. 2014)







## Outline

- ► **Evolution of Manufacturing and PHM**
- ► Changing Big Data Environment and Emerging Technologies on Big Data Analytics, Cyber-Physical Systems, and Industry 4.0
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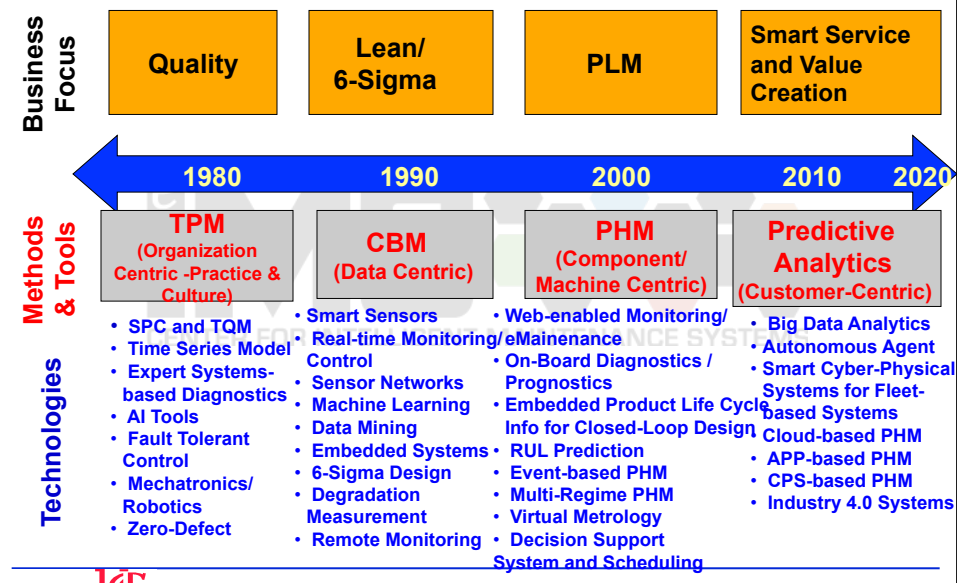
# Evolution of Manufacturing and PHM



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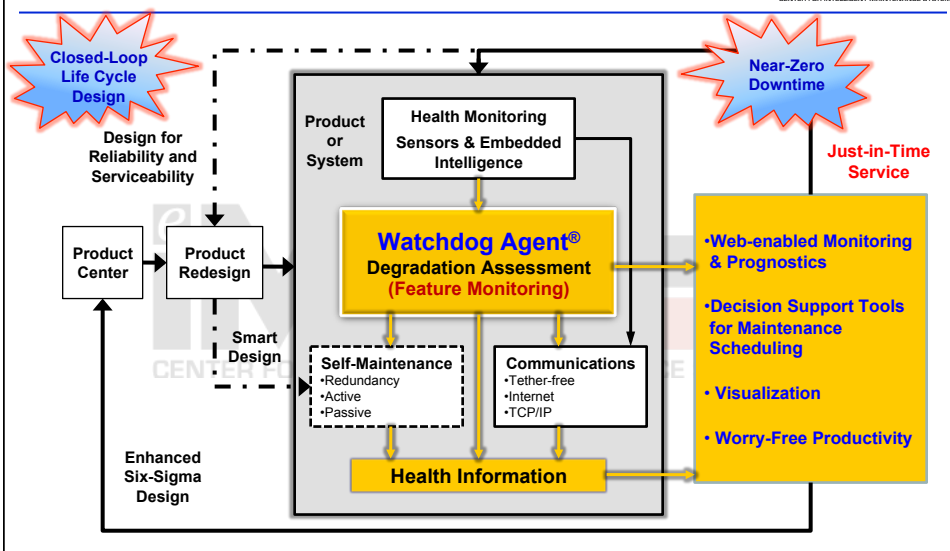
# Maintenance of the Future (2000)




*Watchdog Agent® is a registered trademark of IMS Center.*

IMS 2000



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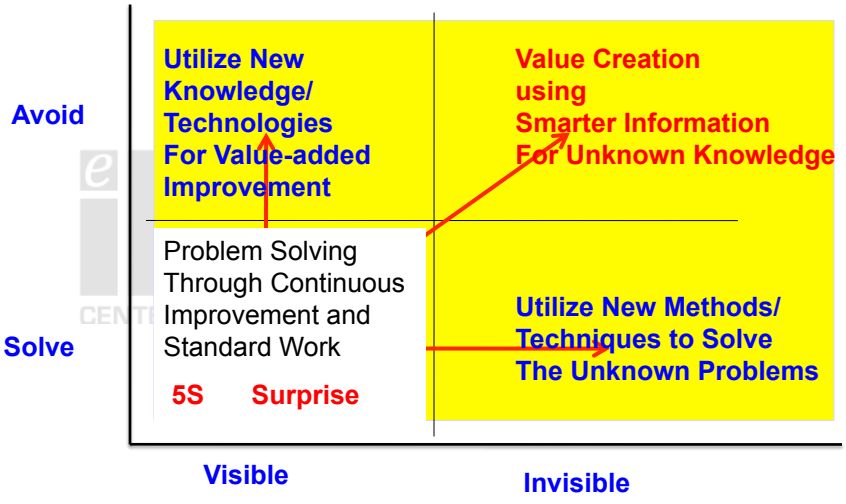
## Competitiveness Transformation Strategy







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# 6Cs in Big Data System

1. Connection --RFID, Wireless, Sensor Networks
2. Cloud – Computing and Data on Demand
3. Cyber— Model and Memory
4. Content/Context – Correlation and Classification
5. Community -- Relationship and Sharing
6. Customization – Service and Value



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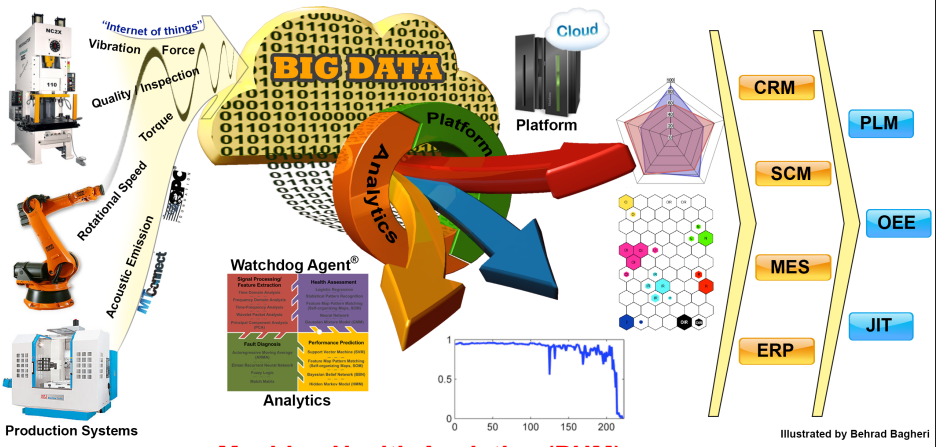
# Smart Manufacturing Analytics

*Information on Demand (meaning and content)*




**Machine Health Analytics (PHM)**

**Factory Analytics**

Lee, J. Lapira, E. Predictive Factory, Manufacturing Leadership Journal, March 2013.
Lee J, Lapira E, Yang S and Kao A. *Predictive Manufacturing System – Trends of Next-Generation Production Systems*. Intelligent Manufacturing System (IMS) 2013 Symposium, May 21-24, 2013. Sao Paolo, Brazil.

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# What are Cyber-Physical Systems?

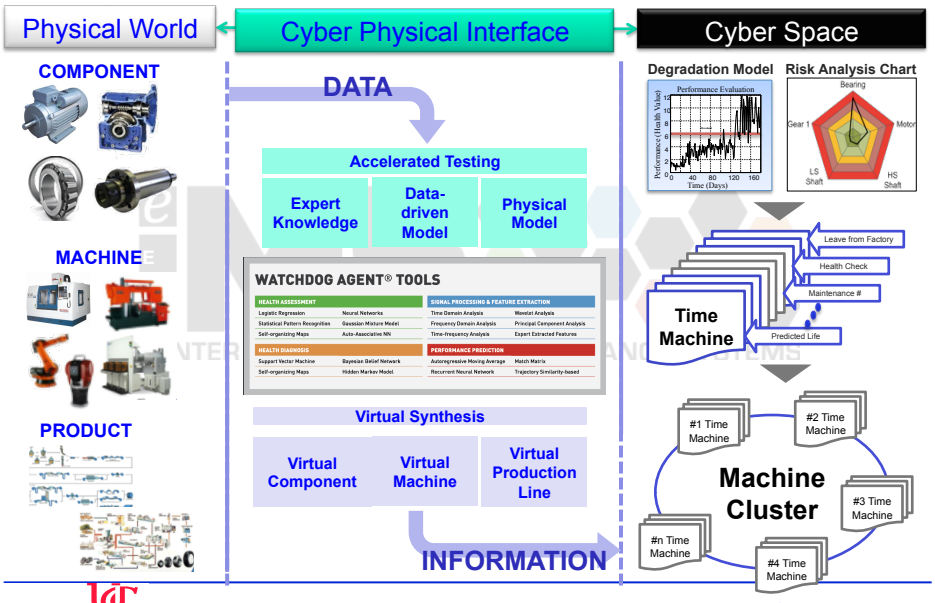
- **Physical**
  - natural and human-made systems governed by the laws of physics and operating in continuous time
- **Cyber**
  - computation, communication, and control that are discrete, logical, and switched
- **Cyber-Physical Systems**
  - systems in which the cyber and physical components are tightly integrated at all scales and levels

Ref: NSF CPS Program, 2007



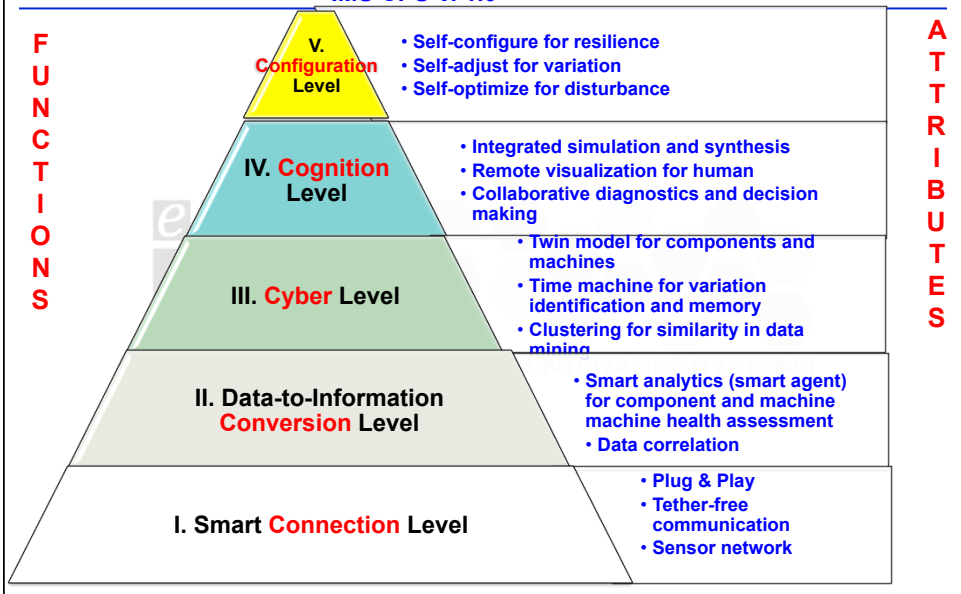


# Cyber-Physical Interface



# Architectures for 5 Levels (5C) of CPS

IMS CPS V. 1.0





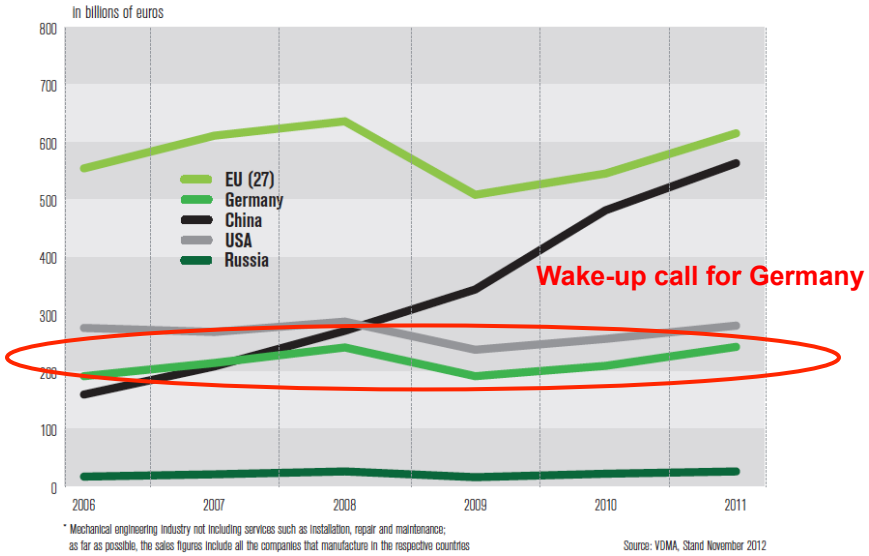



# EU & Germany

# Industry 4.0

## *Internet of Things and Services*

# Germany Global Mechanical Product Sales 2006-2011



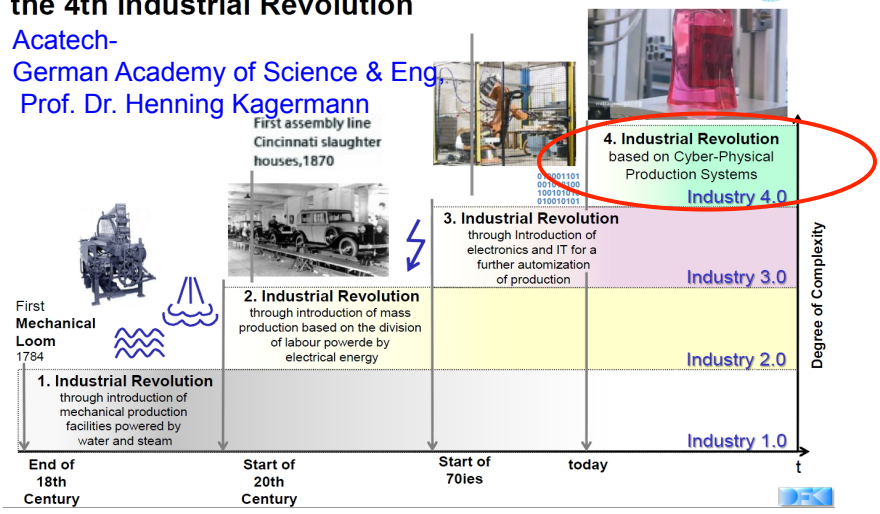





# From Industry 1.0 to Industry 4.0

## From Industry 1.0 to Industry 4.0: Towards the 4th Industrial Revolution

Acatech-
German Academy of Science & Eng,
Prof. Dr. Henning Kagermann




http://www.uberb2b.com/b4b-presents-the-first-industry-4-0-mini-conference/

## Comparison of Industry 4.0 Factory vs. Today's Factory

| | | Today Factory | | Industry 4.0 Factory | |
|---|---|---|---|---|---|
| | Data Source | Attributes | Key Technologies | Attributes | Key Technologies |
| Component | Sensor | Precision | Sensing | Self-Aware | Degradation Measurement |
| Machine | Controller | Quality & Performance | Monitoring & Diagnostics | Self-Predict Self-Compare | Health Prognostics |
| Production Systems | Networked Systems | Efficiency & Productivity | Lean & Green Manufacturing | Self-Reconfigure Self-Optimize | Worry-Free Production |

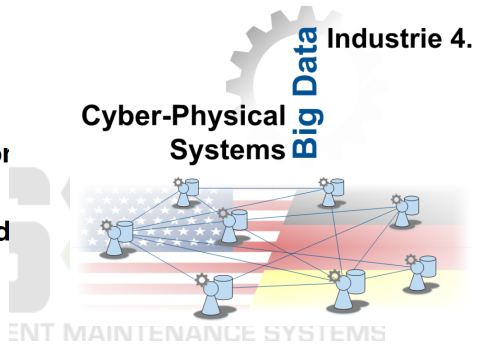
Jay Lee, Germany Harting Tech New 26 ,2013




## 1St Germany-U.S. Workshop

### Workshop Program

**1st German-U.S. Workshop or**
**Predictive Analytics,**
**Cyber-Physical Systems, and**
**Industrie 4.0 in**
**Big Data Environments**




Technische Universität Müncher
Garching near Munich,
17 – 18 November 2014

Birgit Vogel-Heuser,
*Technische Universität München*

Jay Lee, *University of Cincinnati*

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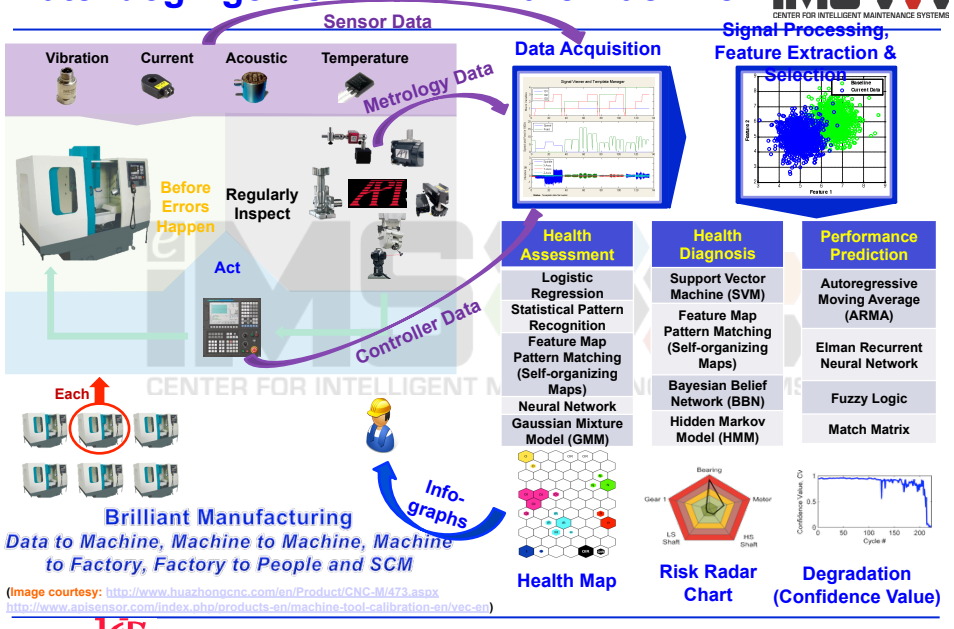
# Watchdog Agent® → Self-Aware Machine




(Image courtesy: http://www.huazhongcnc.com/en/Product/CNC-M/473.aspx http://www.apisensor.com/index.php/products-en/machine-tool-calibration-en/vec-en)

## Implementation of PHM Analytics

### Step 1:

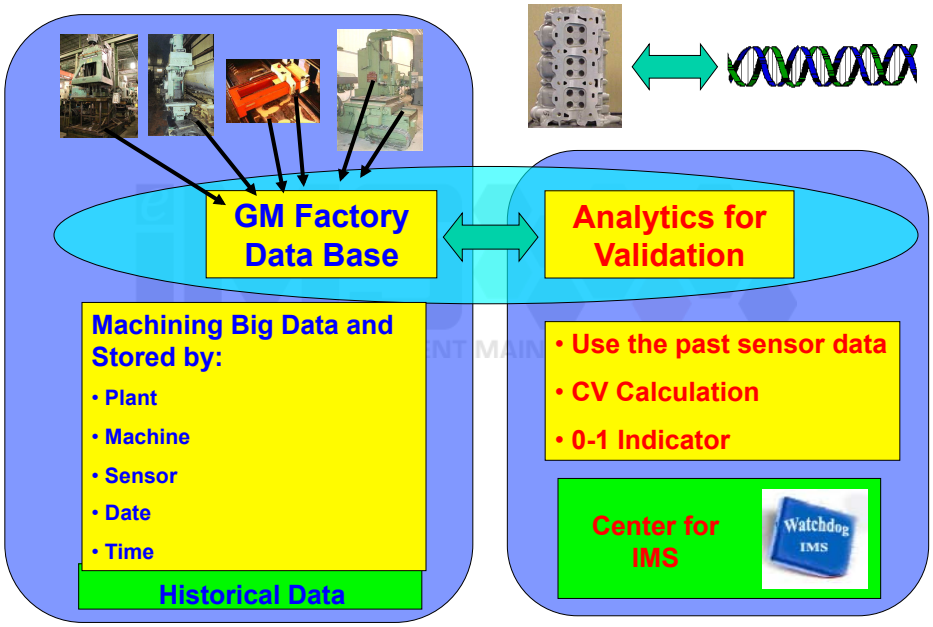
### Understand and Validate the Past Issues





### GM E-Manufacturing Testbed
### St. Catherine Assembly Plant, Canada

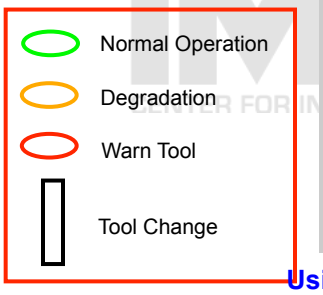
## GM E-Manufacturing Testbed (2002)

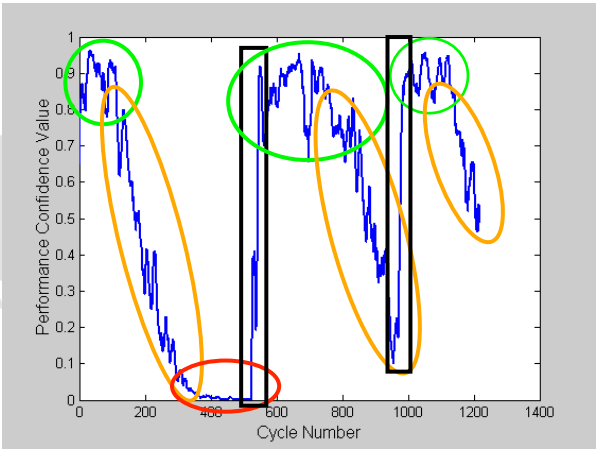



## Analytics for Machine Tooling Health

• Spindle load sensor in a machining center.

• 1218 boring process cycles.




**Using Logistics Regression algorithm to convent past current signals to tool life degradation**

# Data Challenge

1. NASA PHM Data Depository

2. PHM (Prognostics and Health Mgt) Data Challenges Competition:

2008 (1st and 3rd)
2009 (1st Professional Group) & (1st, 2nd, 3rd Student Group)
2010 (3rd)
2011 (1st and 3rd)
2012 (3rd)--
2013 (3rd, 4th, 5th)
2014 (1st).




# Implementation of PHM Analytics

**Step 2:**
**Don't Just Listen to Customer but Do Understand the Issues**
**&**
**Prioritize the Issues**
**Focus on the High-Impact Things**

## IMS, Toyota, NI, Rockwell Automation Partnership

## Toyota Motor Manufacturing, KY

CENTER FOR INTELLIGENT MAINTENANCE SYSTEMS



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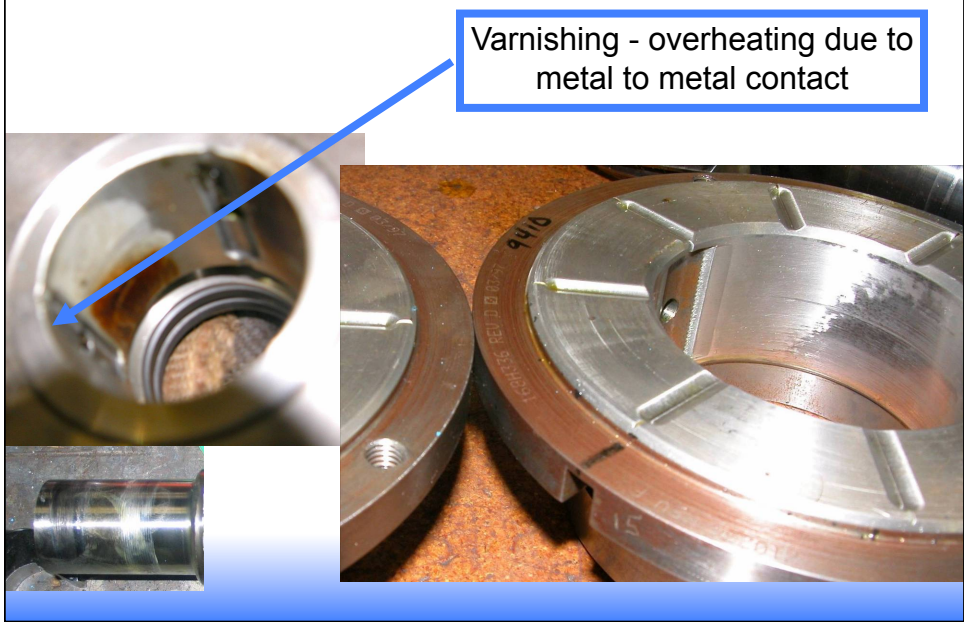
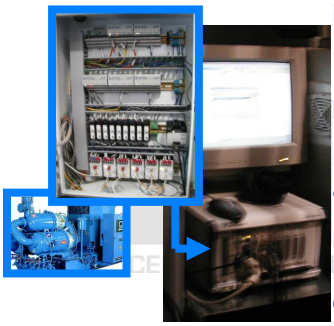
## Problems on Compressor Bearing



# Overview of Work



**Sensors installed**

**Data acquisition installed**

**New IGV installed**

**IGV & surge testing**

**Data collected &distributed**

**Data analyzed internally & by IMS center**

**Project documentation**

**Preliminary surge model**

**Key Areas of Concentration**

Data Collection & Analysis

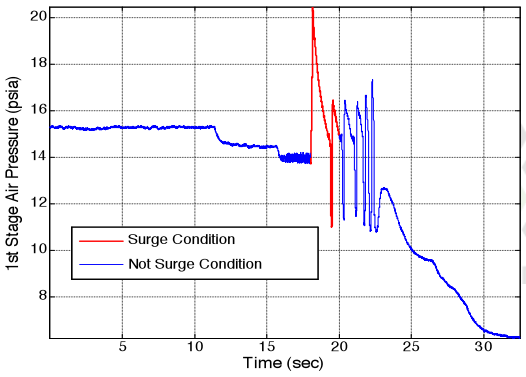
NATIONAL INSTRUMENTS

- PXI hardware on loan to IMS center
- Donation of time: Onsite troubleshooting
- Expert support: DAQ

Rockwell Automation

- Loaned Hardware
- Expertise in sensor troubleshooting

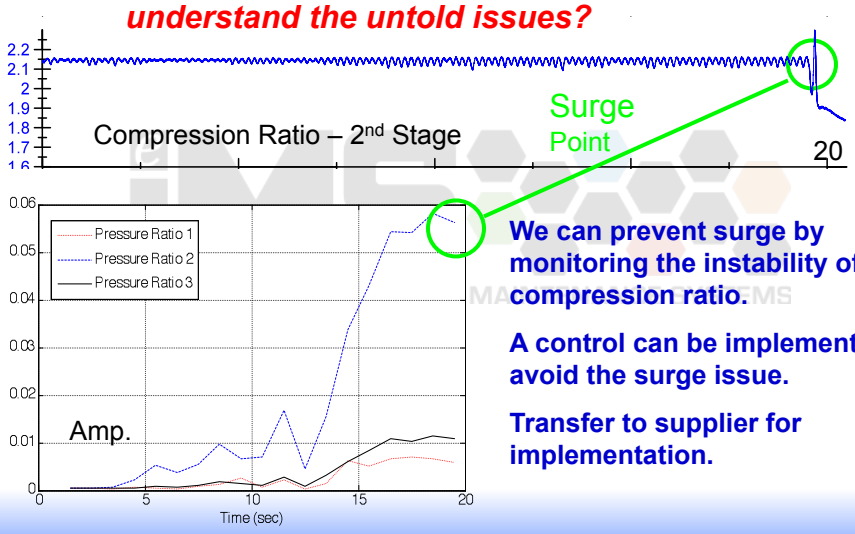
# Compressor Surge Modeling: Identifying Data Vectors using PCA




| | August 8th - Surge Test 001 | |
|---|---|---|
| | not surge | surge |
| Time (sec) | 2.2-13.2 | 14.2-19.854 |
| IGV feedback (%) | 23.7297 | 22.6394 |
| Press 1 (psig) | 15.2714 | 15.258 |
| Press 2 (psig) | 49.5846 | 49.3911 |
| Press 3 (psig) | 123.5615 | 123.3989 |
| Airflow (scfm) | 4720.3 | 4618.2 |
| Current (A) | 150.765 | 148.9399 |
| IGV command (%) | 21.5355 | 20.5417 |
| BOV (%) | 99.8637 | 99.8637 |
| humidity (RH) | 54.1564 | 54.3121 |
| temp 1 (F) | 279.2926 | 279.4476 |
| temp 2 (F) | 255.841 | 256.3763 |

## What did we learn?

***Work with maintenance expert and suppliers to understand the untold issues?***




**We can prevent surge by monitoring the instability of the compression ratio.**

**A control can be implemented to avoid the surge issue.**

**Transfer to supplier for implementation.**

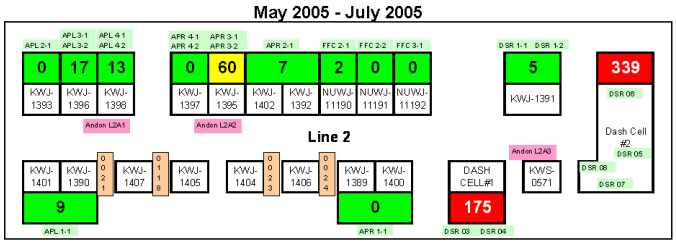
TOYOTA

# Predictive Robot Maintenance at Toyota Georgetown, KY

## MR50% in 2008

# Robot Health Map by Location

- Show whether certain areas (of process) were failing more often than others.
- Display bottlenecks of the process.




**Colors for Line Stop Data**

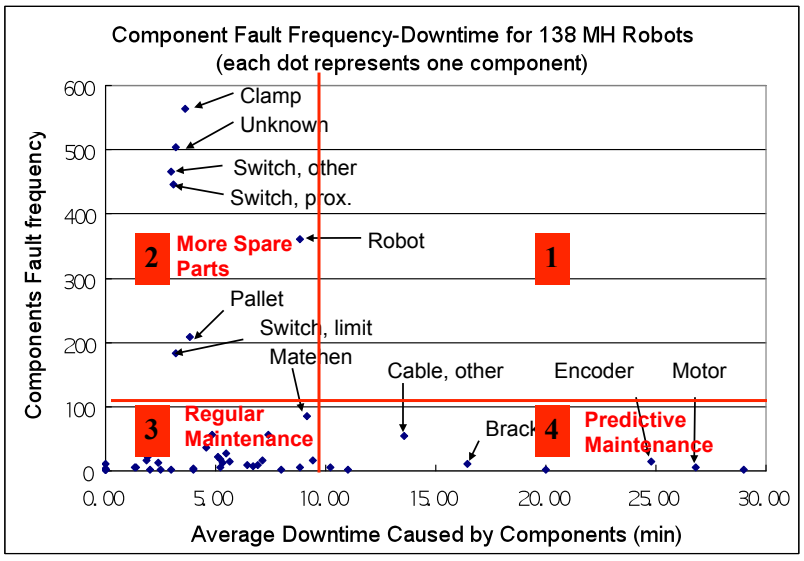
- Less than 30 minutes
- Greater than 30 and less than 120 minutes
- Greater than 120 minutes

Dash Cell #2 /#1 and KWJ-1395 units cause most line stop time

- Robots from different manufactures
- Used Zone 3A as an example
- Based on line stop time




# Critical Components



## Robot Health Monitoring

## Nissan Manufacturing Plant
## Smyrna, Tennessee

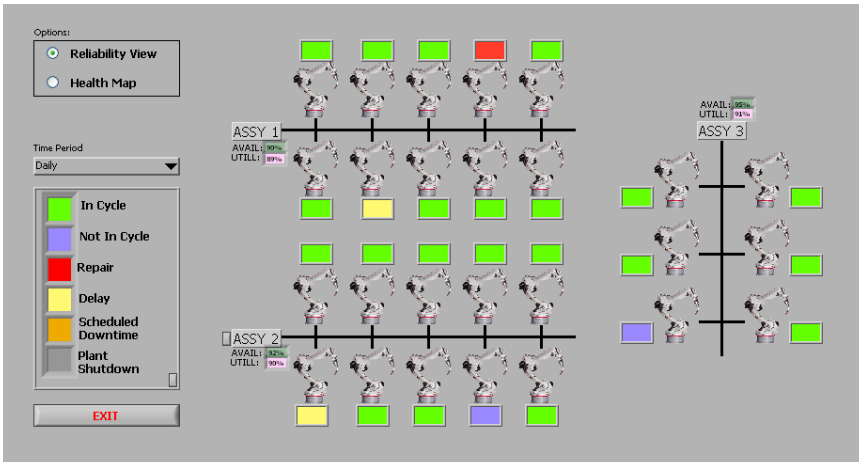



## Robot Health Assessment -Example

**Health Assessment Result for Third Servo-motor Robot Joint**

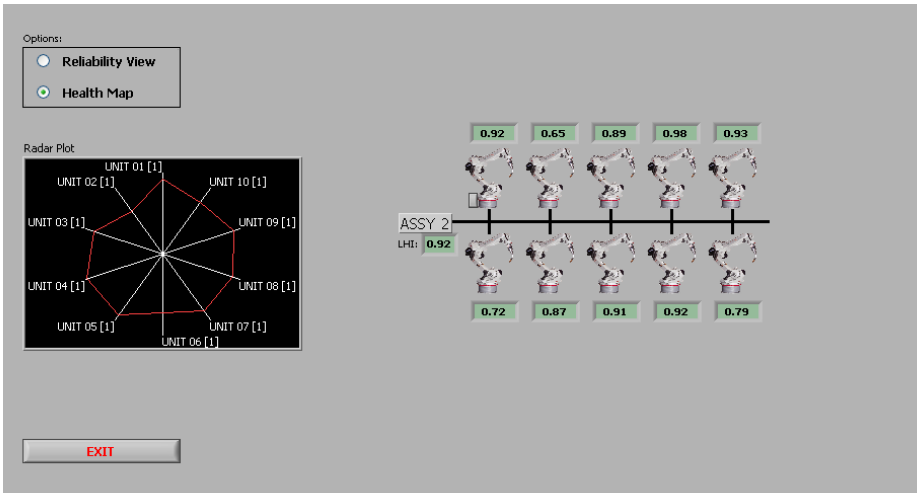

- Applying the IMS **logistic regression algorithm** included using the moving average and RMS torque value of the low-speed regime segmented data set as the two features used in training the model using the unacceptable (degraded) state data and acceptable (healthy) state data.
- The results of applying this method for the third robot joint servo motor are shown above, which shows that early signs of degradation can be seen as early as **3 weeks** in testing cycle 125 but failure does not actually occur until cycle 220.

# Screenshot of Reliability --Before

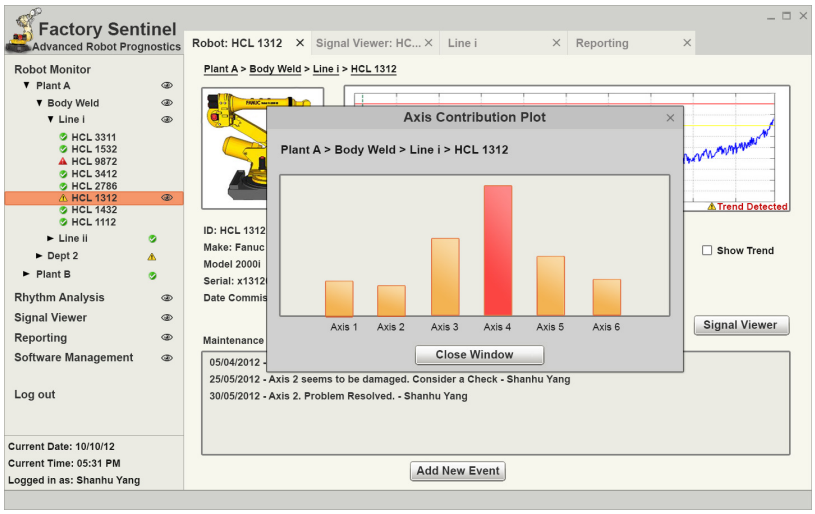





# Screenshot of Health Map--After



## *Factory Sentinel*—Predictronics New Product




Ref: Predictronics




## Implementation of PHM Analytics

### Step 3:

### Integrate Machine Data, Historical Data, and Expert Experiences for Improved PHM Value

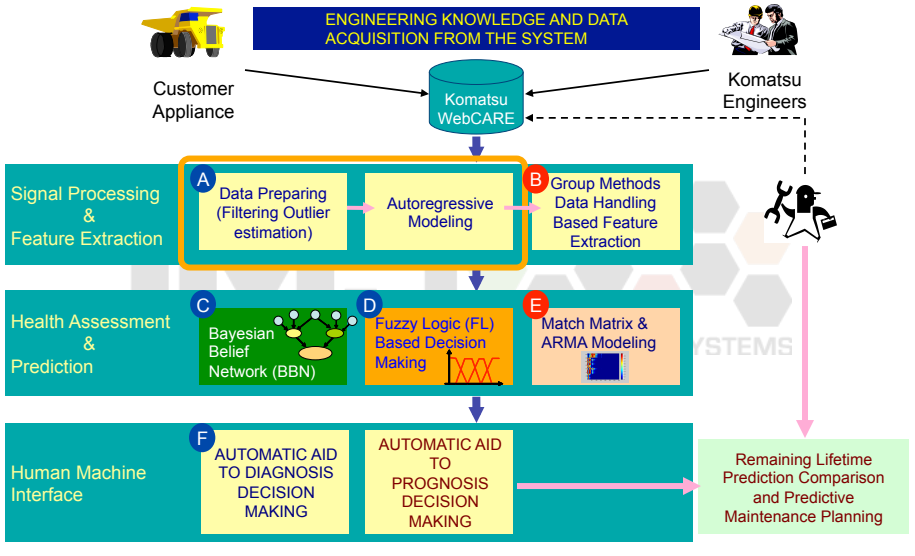
# Intelligent Maintenance of Komatsu Mining Equipment and Diesel Engines 2005-2007

## *(Komatsu Engineer Stay at IMS for 18 Months)*



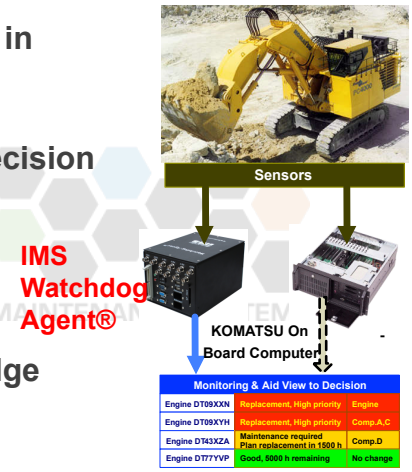


## Prediction of Remaining Lifetime of Engines



# IMS vs. Komatsu Approach

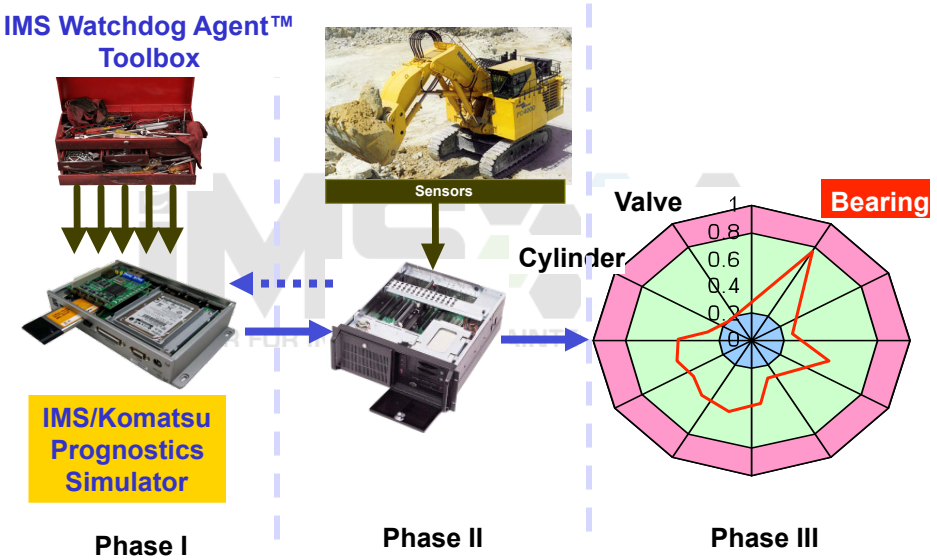
- to increase quality of data in Komatsu database
- to enable more advanced predictive maintenance decision making base on analytical reliability models
- to achieve intelligent maintenance excellence
- and to implement knowledge based decision making approach







# IMS/KomatsuTestbed 2005-2007



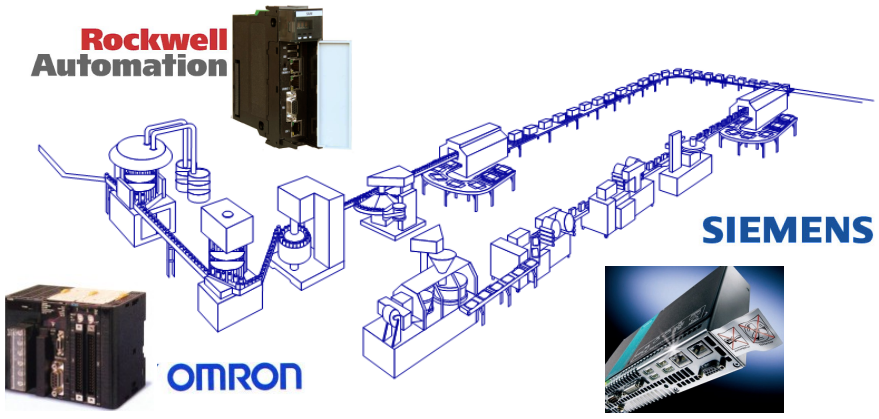
## Implementation of PHM Analytics

### Step 4:

### Embedded Smart Analytics with Any Systems (Controller, Server, Cloud, Components, etc.)




## Embedded Prognostics




**Reconfigurable Prognostics Systems**

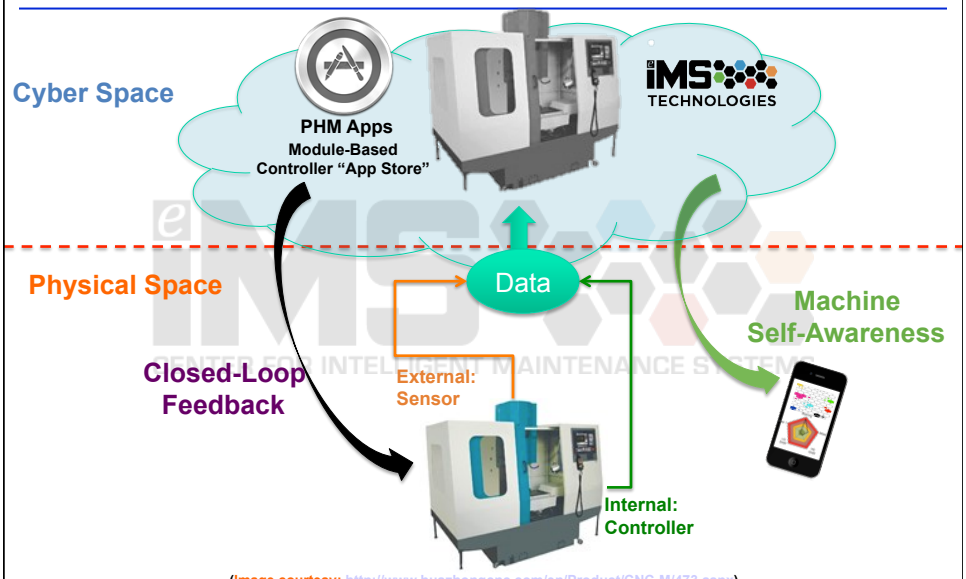
Enable Zero-Breakdown Productivity

## New Next of PHM Analytics

### Using Cyber Physical Systems




## IMS Self-Aware Machine Tools




(Image courtesy: http://www.huazhongcnc.com/en/Product/CNC-M/473.aspx)

# Industry 4.0 Machine Demonstration

# at

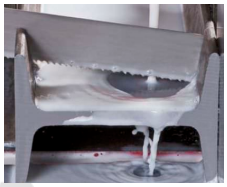
# IMTS Chicago

# Sept. 2014





## Case Study with Cosen Band Saw Machine

*http://www.directindustry.com/prod/starrett/band-saw-blades-11639-534692.html*

**Domain Knowledge**

- **Failure Modes**
- **Cutting Parameters**

**Blade Types**
- OEM
- Material
- Tooth configuration

**Material**
- Geometry
- Cross-section
- Hardness

**IMS PHM Tools**

- **Signal Processing**
- **Health Assessment**
  - Adaptive clustering
  - Statistical pattern recognition
- **Prognostics**
  - Utilization based prediction
  - Proportional hazard model

**CPS objective**

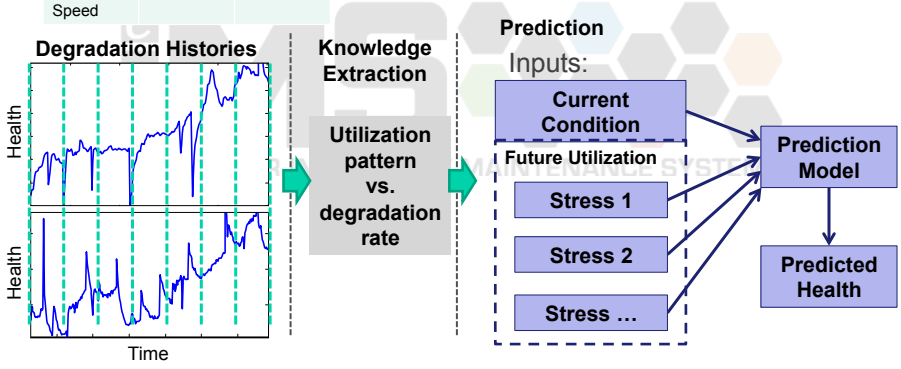
» **Maintenance & utilization suggestion**

» **Product quality control**

# On-Machine Agent for Utilization based Prognostics

Rotating machine:

| | High Load | Low Load |
|---|---|---|
| High Speed | Rate 1 | Rate 2 |
| Low Speed | Rate 3 | Rate 4 |



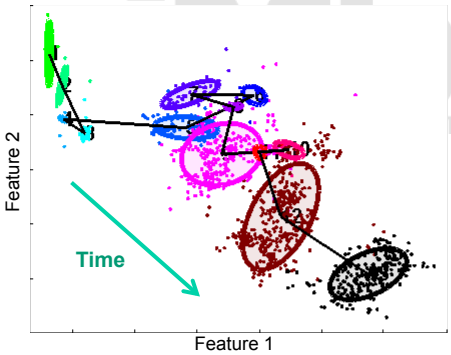




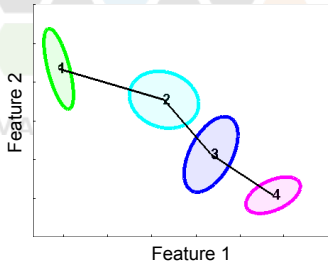
# Band Saw Degradation Analysis Results

- After each cut, features are extracted as health indicators:
  - Energy percentage of frequency range [3750 4000] Hz
  - Blade downward pressure
- After each feature extraction, adaptive clustering is used to perform machine health assessment in real-time.

Step 1: on-line adaptive local clustering



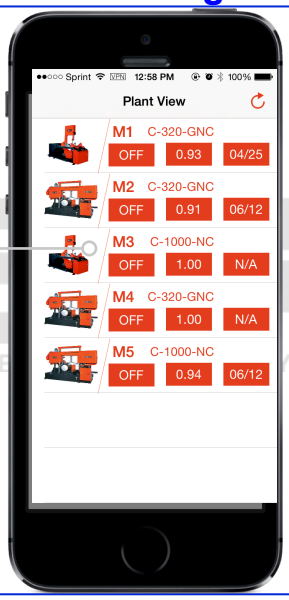

Step 2: hierarchical clustering




Step 3: prediction and decision making under each cluster

# Machine Mobile Agent (APP)- New Way of Machine Management

List of Machines in factory plant with abstract information about each machine including:
working status, Latest health value and last timestamp of historical data

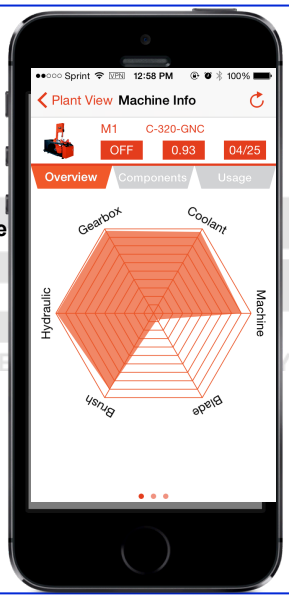




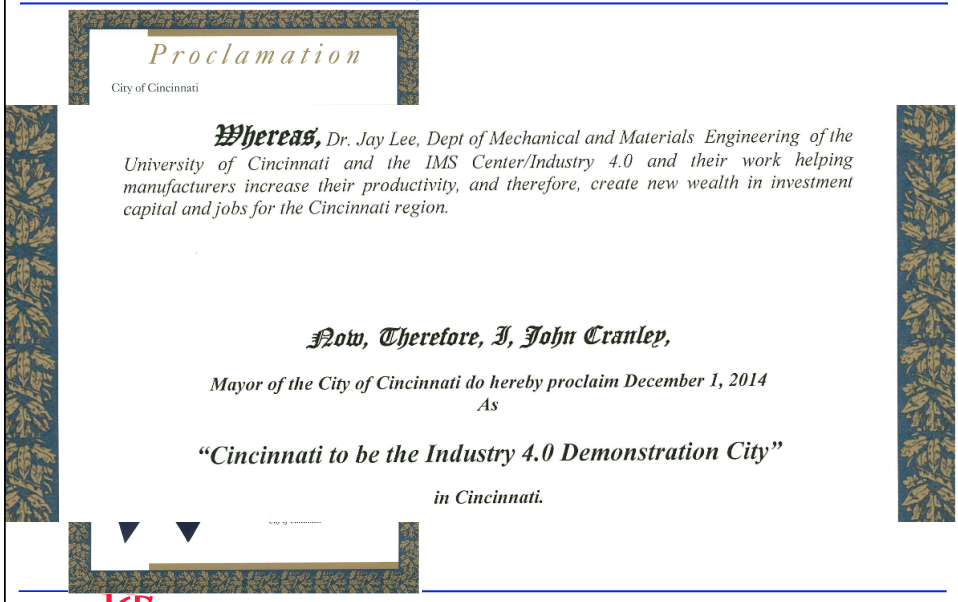


# Cognition & Analytics on Demand

By clicking on each machine, detailed information of that machine will be displayed.
In the first section (overview) a radar chart for overall health status of machine components is displayed



# Cincinnati as Industry 4.0 City, Nov. 5, 2014



Proclamation

City of Cincinnati

**Whereas,** Dr. Jay Lee, Dept of Mechanical and Materials Engineering of the University of Cincinnati and the IMS Center/Industry 4.0 and their work helping manufacturers increase their productivity, and therefore, create new wealth in investment capital and jobs for the Cincinnati region.

**Now, Therefore, I, John Cranley,**

*Mayor of the City of Cincinnati do hereby proclaim December 1, 2014 As*

*"Cincinnati to be the Industry 4.0 Demonstration City"*

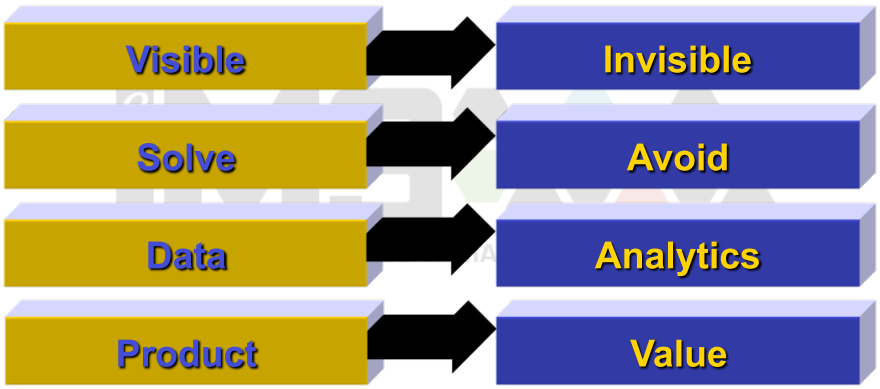
*in Cincinnati.*





# Conclusions

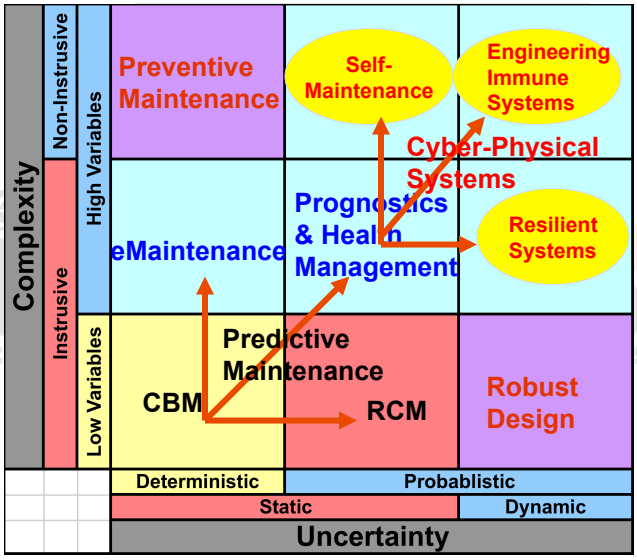
# Transformation







# Maintenance/PHM Transformation Map




Ref: Jay Lee, *Annual Reviews in Control*, Volume 35, Issue 1, April, 2011.

## Key Value of Predictive Big Data Analytics

***Big Data is to Create No-Data Decision***

***for Worry-Free Productivity***





# Thank You !

**New Book on**
**Cyber Physical Systems in Manufacturing,**
**Industrial Press, 2015.**

**www.imscenter.net**

Google Jay Lee, Prognostics, E-Manufacturing, E-Maintenance, Dominant Innovation, Cyber Physical Systems, Industrial Big Data Analytics