



A Two Day workshop on Aircraft Health Management (AHM–2023) during 22-23 June 2023 organized by Aeronautical Development Agency (ADA), Bangalore



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Senior Officers from ADA, DRDO, ISRO, IAF, IN, Academicians from Prestigious Institutions, Experts from National Labs, Industry partners, Special Invitees(India & Abroad), Distinguished Speakers, Distinguished Delegates, Organisers of AHM-2023, Ladies & Gentlemen

.....Very good morning

Technology Competencies Required to Create an Effective IAHM Program

22 June 2023 at ADA, Bangalore

Dr V Bhujanga Rao, FNA, FNAE

Founder President

Condition Monitoring Society of India (Estt 2003)

Former DS & DG, DRDO

Former ISRO Chair Professor NIAS

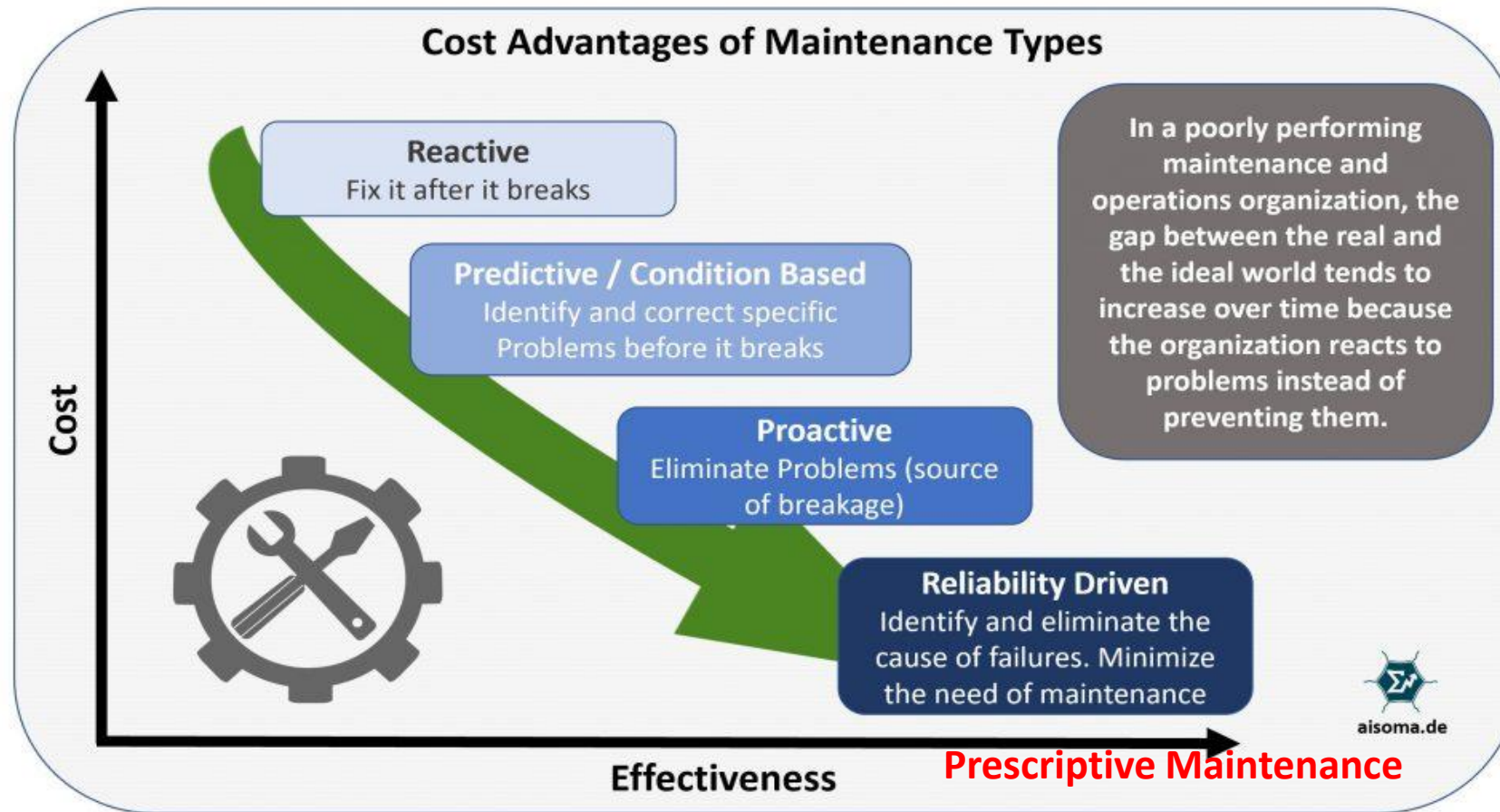
Visiting Professor, NIAS

Chairman, KIMS Foundation & Research Centre, Hyderabad

Content of My Talk

CBM in I4.0 ecosystem
Contemporary Studies
IAHMS as envisaged today
Opportunities & Challenges
Concluding Remarks

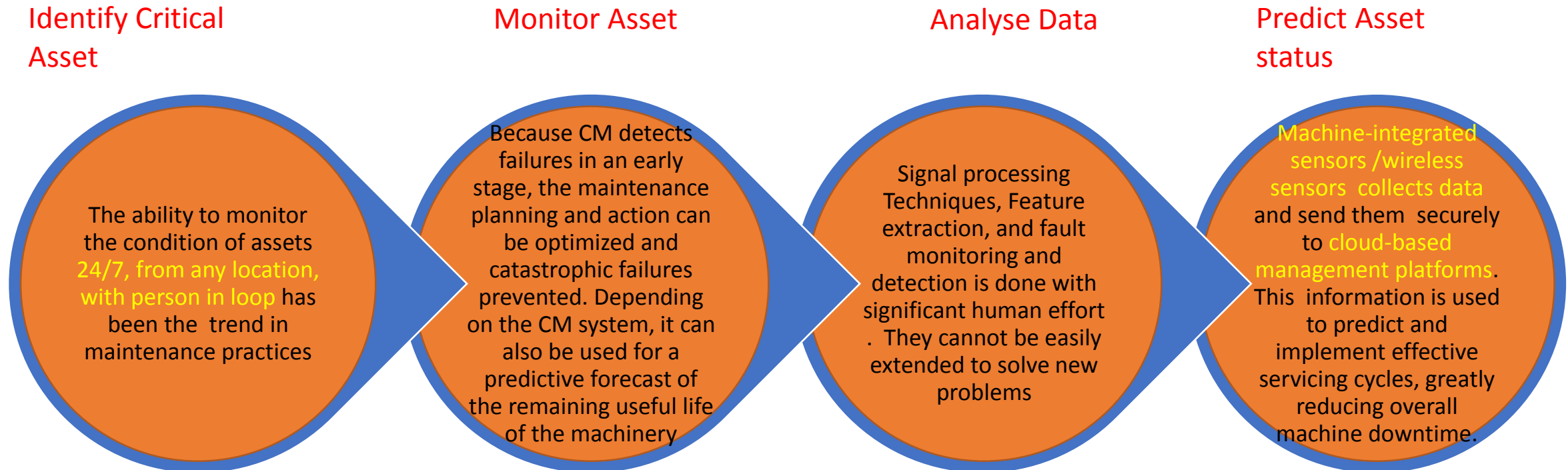
Why Condition Based Monitoring gained so much importance!



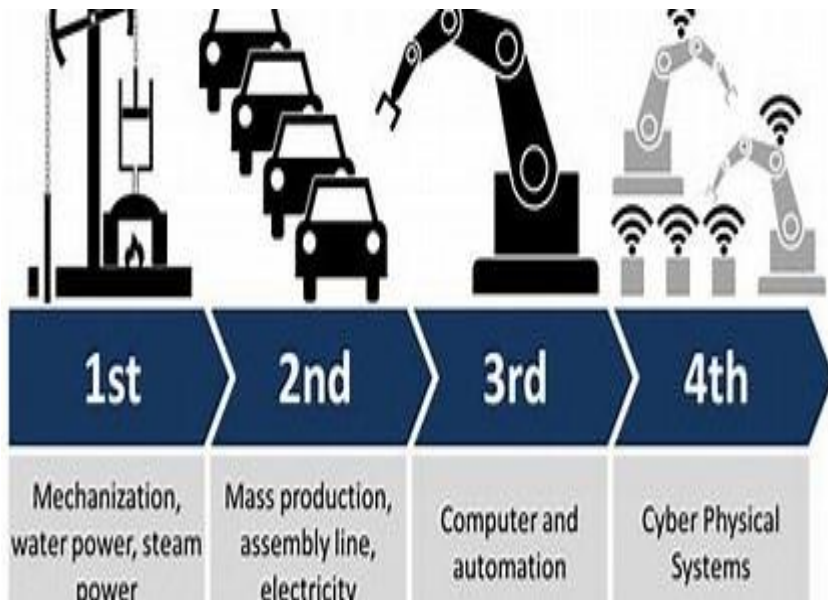
- Product design improvements
- New product development
- Maximize production output
- Outage prevention
- Smart maintenance
- Extend machinery lifespan
- Optimize inventory of spares
- Product reliability
- Focus on preserving safety by avoiding grave malfunctions

Condition Based Maintenance : Prior to Industry 4.0

Man in the Loop System

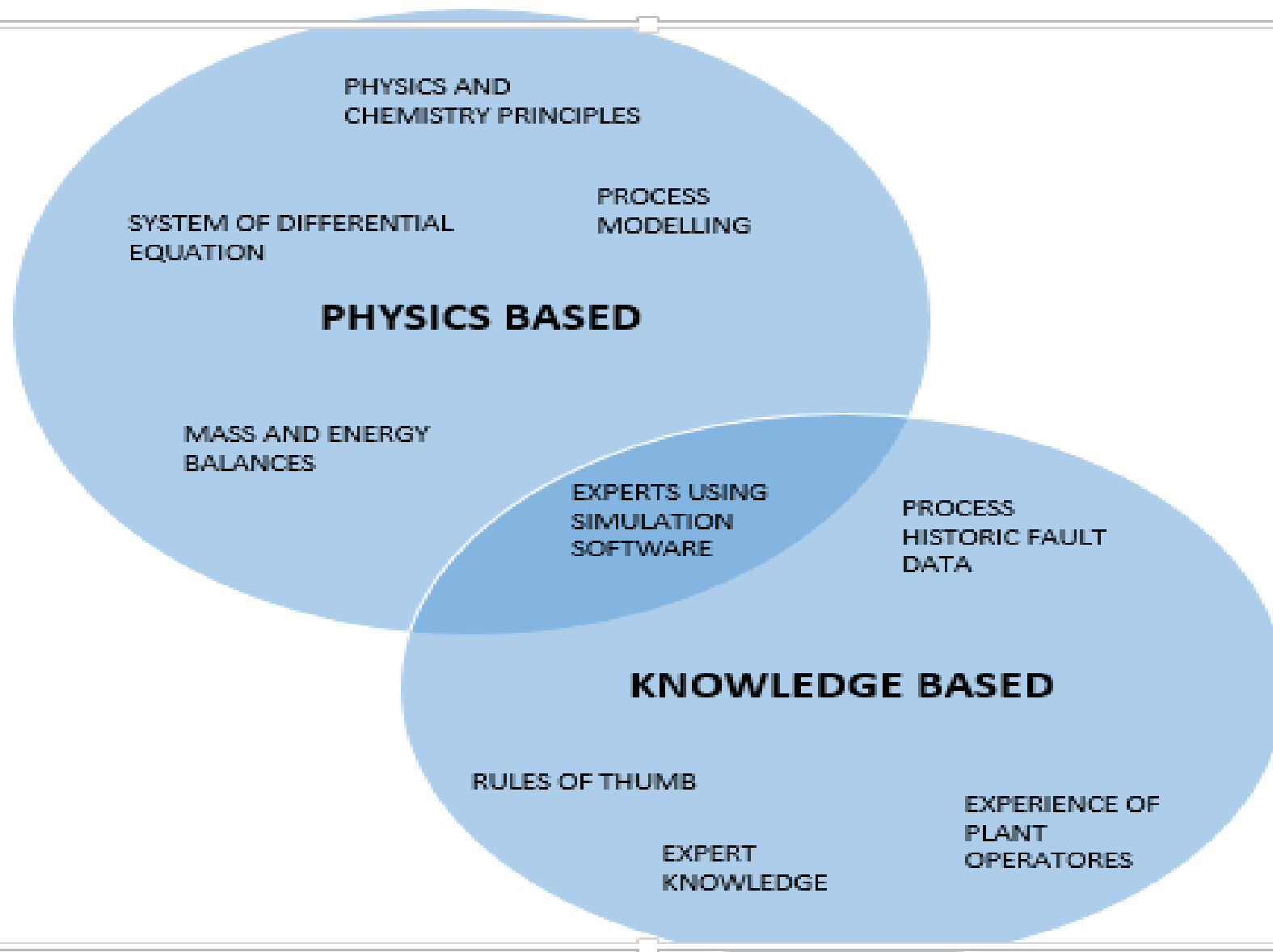


Condition Monitoring in Industry 4.0 environment



- **Smart Sensors** allows continuous condition monitoring.
- Data facilitates intelligent decisions using **predictive data analytics**.
- **IIoT** fulfil the four main functionalities consist of real-time monitoring, controlling, optimization, and autonomy.
- **IIoT enables transforming data to information, knowledge and wisdom (DIKW)** for real-time monitoring, notification, and predictive maintenance at the product and service level in a smart environment
- Today assets can be operated at their peak performance while implementing a condition monitoring maintenance plan.
- **Massive data is generated in real time** in various systems for Condition Monitoring purpose.
- **AI is responsible for selecting which machine learning models** are applied and maintaining these models over time.

BEFORE INDUSTRY 4.0



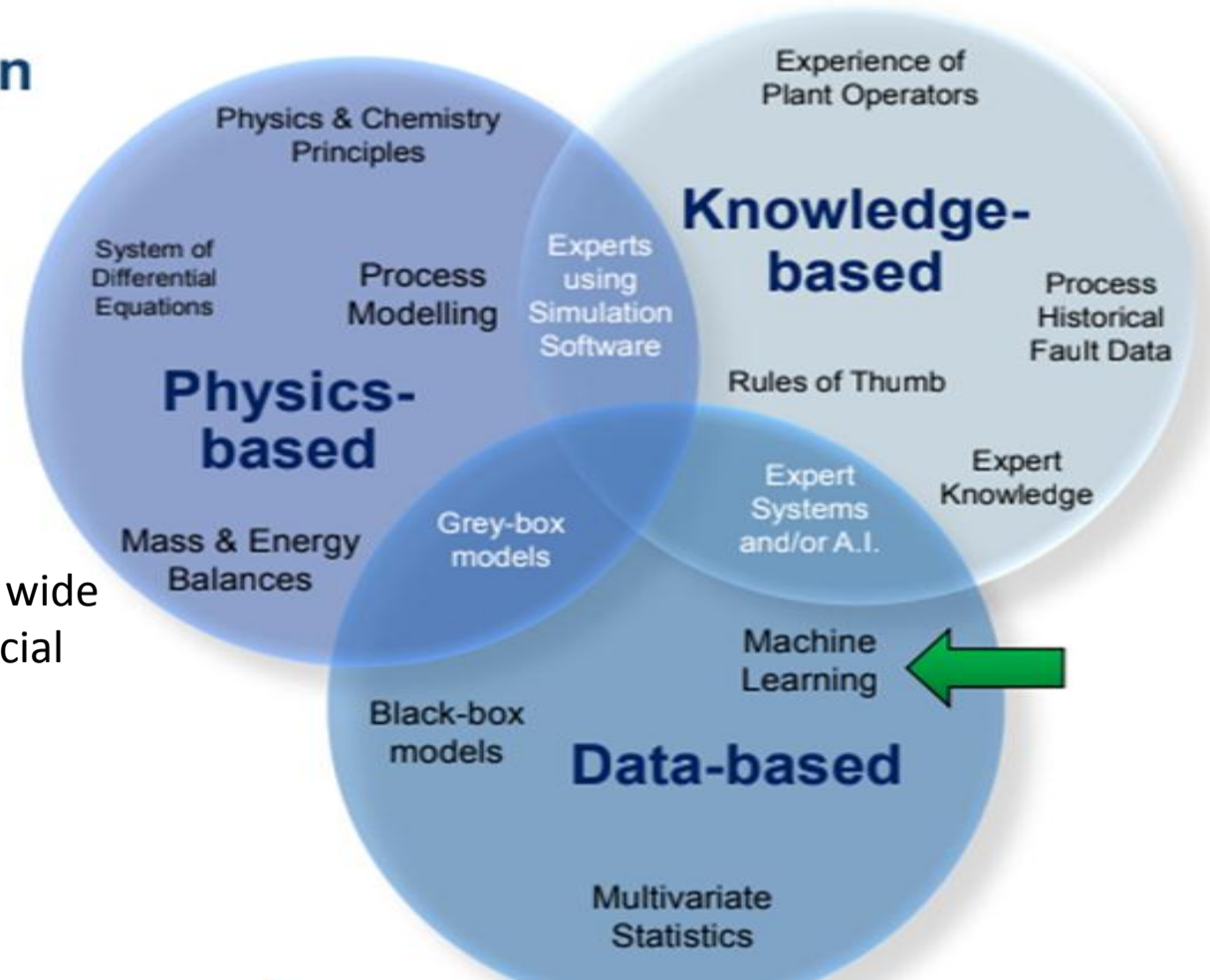
IN INDUSTRY 4.0



General Condition Monitoring Methodology

Train a model

The combination of physical things, a wide range of networks, IoT, big data, artificial intelligence (AI), Cloud capacity and process gives rise to smart systems



Digital Transformation leading to I4.0

- Cloud computing
- Edge computing
- Fog Computing
- Big data
- IIOT
- Predictive analytics
- 5G technology
- AI/ ML/ Deep learning
- Cognitive computing
- Computational Design
- Cyber Physical System
- Design thinking
- Customer/ User Centric world
- UX/UI
- 3D printing
- Agile methodology
- AR/VR
- Digital twin
- Smart Home/ Factory
- Smart manufacturing
- IOT
- Block Chains



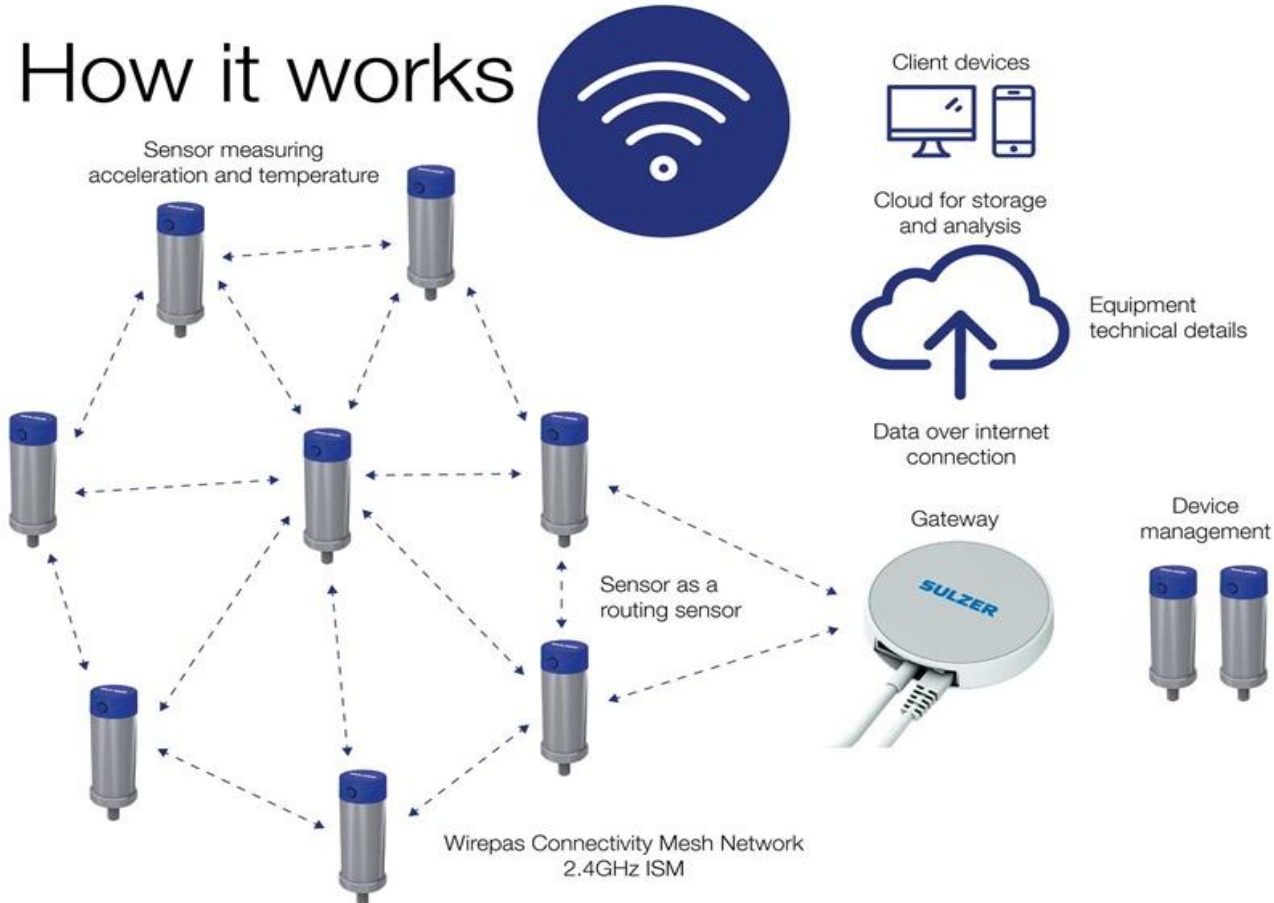
INDUSTRY 4.0 with CBM as centre Pillar

Advances in sensor technology

Machine Doctor wifi is a completely wireless **battery-operated edge sensor that uses wifi routers to take data to the cloud for analysis.** It measures 6 parameters in one i.e Vibration 3D, Acoustic Emission, Surface Temp, Humidity, True RPM & Magnetic Flux. Comes with Magnetic Mount, Stud Mount or Adhesives installation options.

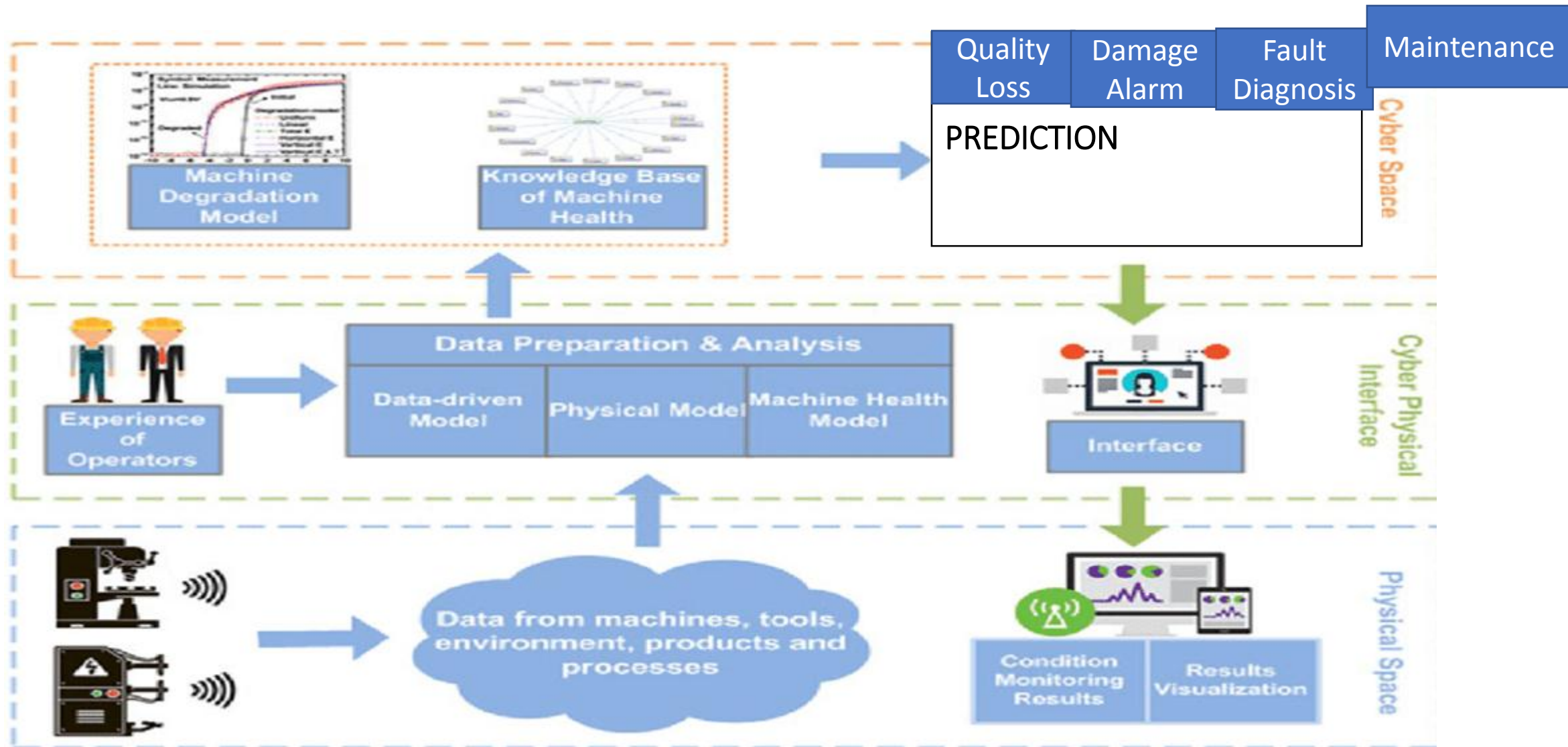


Wireless Sensor Condition Monitoring



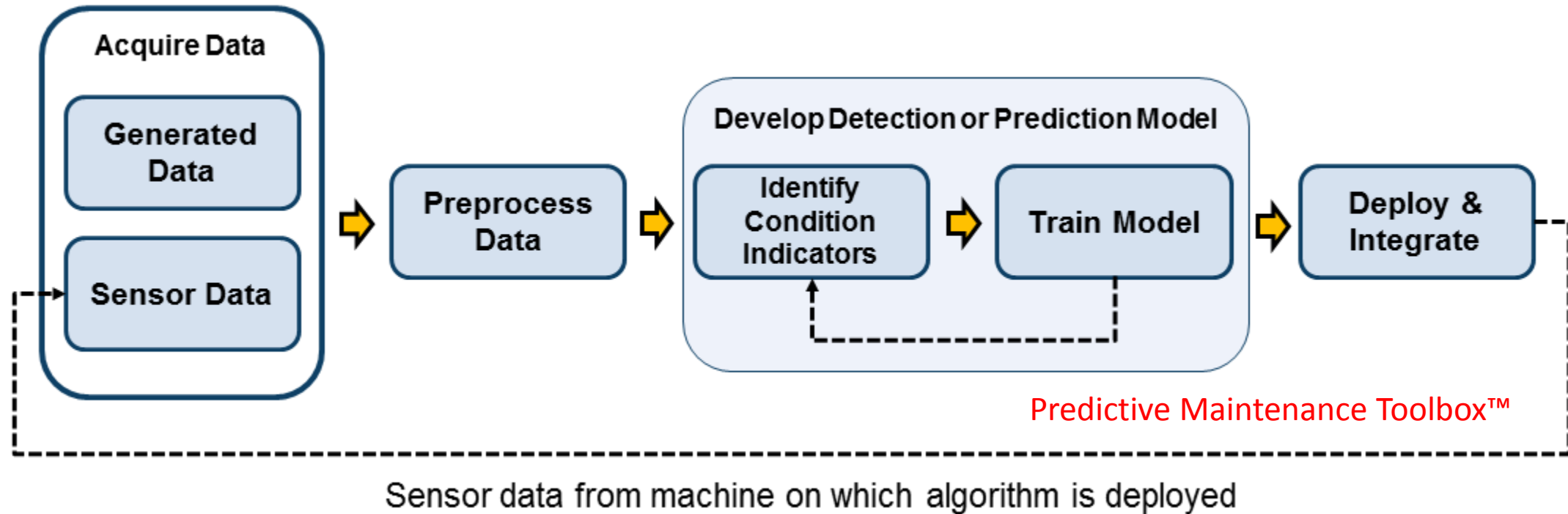
- Wireless sensor networks are very useful for Condition Monitoring of rotating components like for helicopter rotor blades, turbine blades, wind mill blades etc.

A condition monitoring task performed by an ICMS

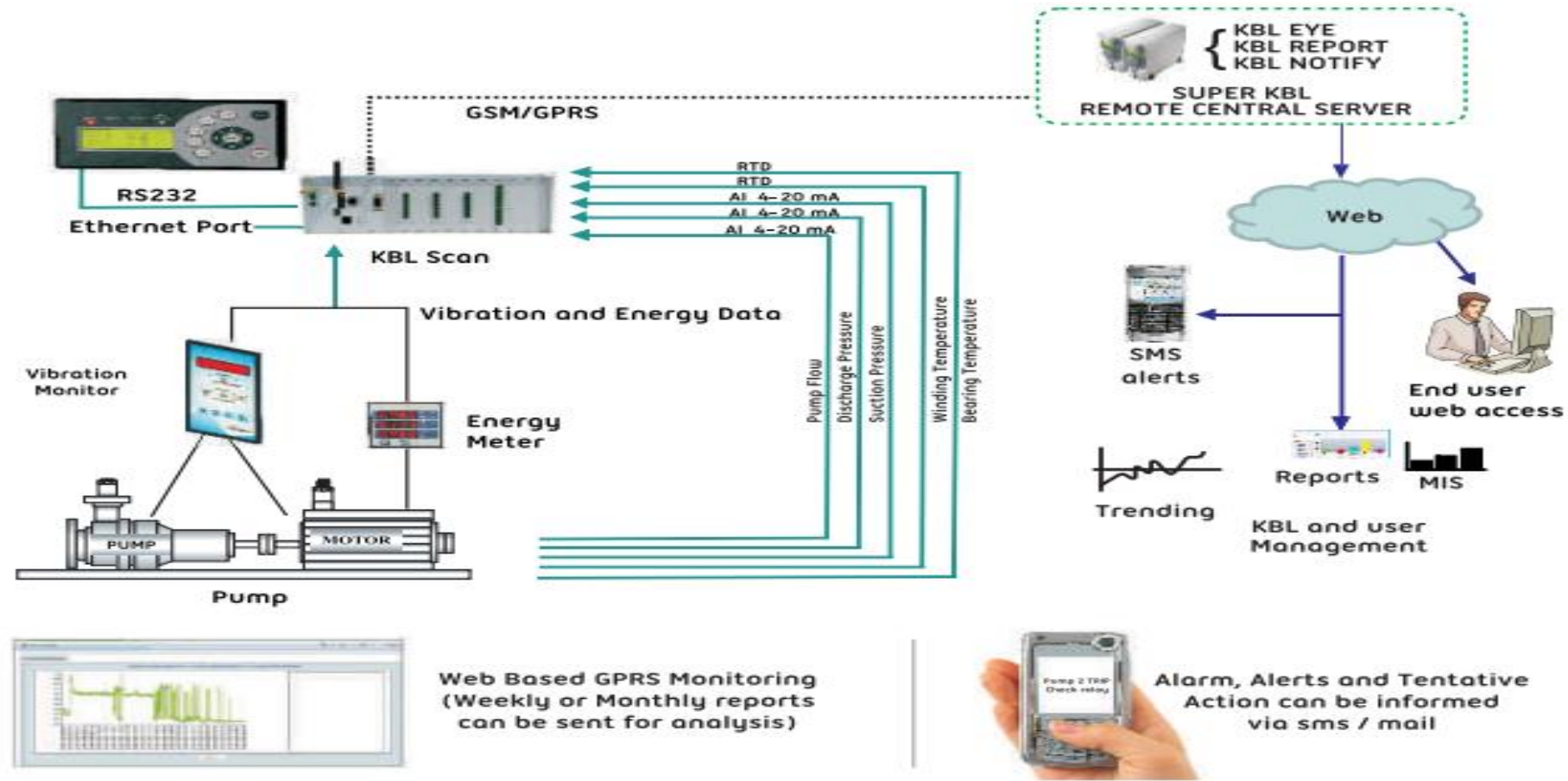


Algorithms for Condition Monitoring and Prognostics

Workflows for Algorithm Development

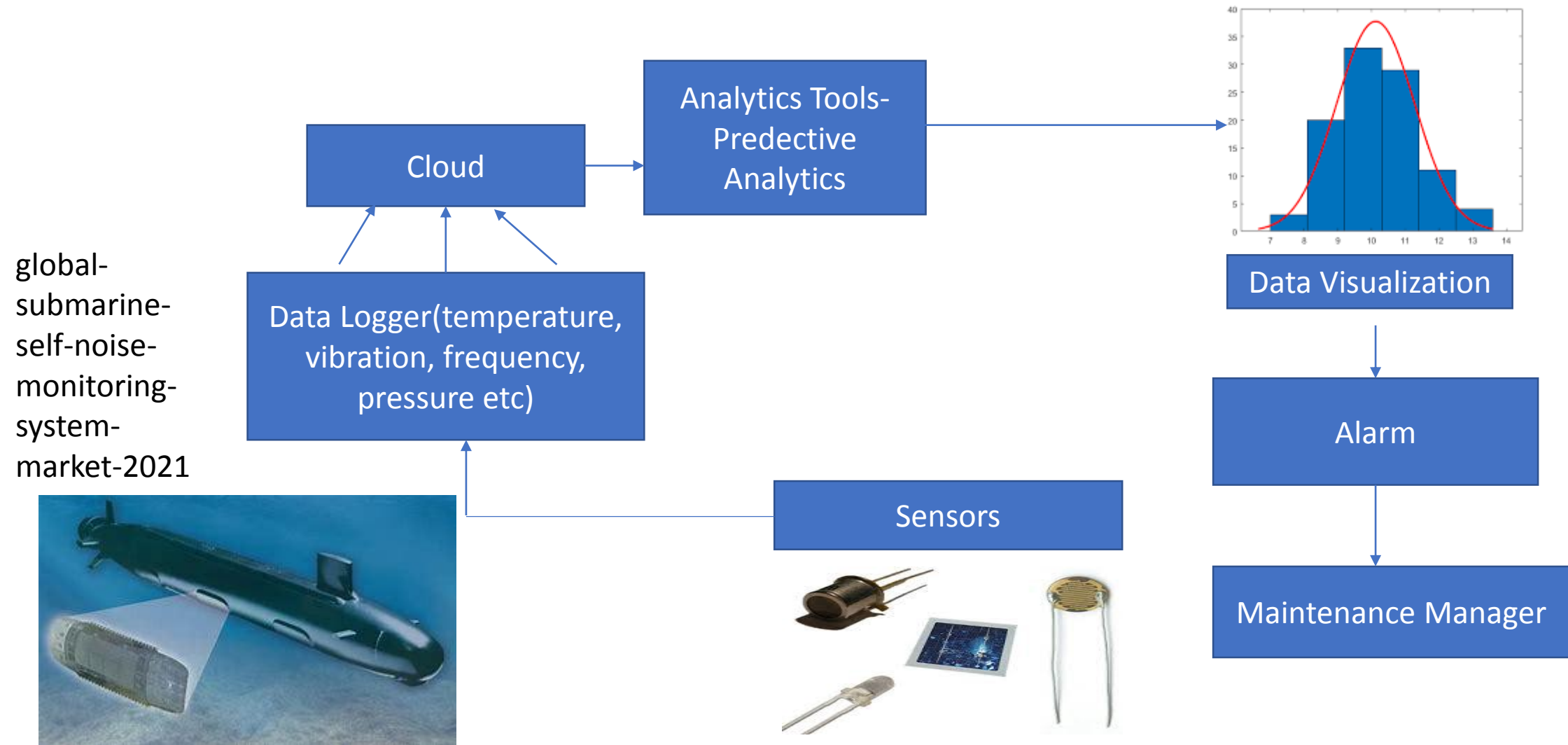


Condition Monitoring as Practiced in Industry today

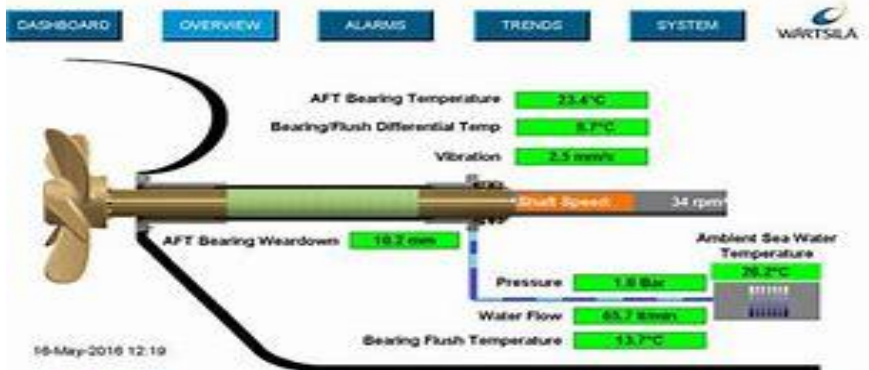


Condition Monitoring- System Architecture

Precursor Technology



Condition Monitoring for Maritime Operations



- Monitoring the health of critical assets such as thrusters, generators, dredging equipment, cranes and other important machines in a marine environment poses a number of specific challenges.
- Marine and offshore installations are exposed to harsh conditions and need to be designed so they can withstand this exceptional environment.
- Data communication from vessel to shore can't be done through wired networks, so data optimisation and remote access functions need to meet these special requirements.
- Condition monitoring systems, installations and services need to follow Class Approval rules and specific safety requirements in order to be deployed in a marine environment.
- Systems and software need to be powerful, yet easy to use in order to accommodate crew rotation and needs to be integrated into the existing vessel control systems.

Potential topics in Condition Monitoring Technology

Deep learning in condition monitoring
Feature extraction in condition monitoring
Nonlinear Kalman filters and particle filters in condition monitoring
Distributed filtering in condition monitoring
Neural networks-based fault diagnosis
Distributed fault diagnosis in manufacturing systems
Tool condition monitoring
Remaining useful life prediction
Transfer learning in condition monitoring
Few-shot learning in condition monitoring
AI-based machining quality prediction
Continuous time dynamical systems
Fuzzy logic-based condition monitoring
Statistical inference method in condition monitoring
Semi-supervised and unsupervised learning in condition monitoring

CBM +

CBM is expanded and termed CBM+, which shall be used as the principal consideration for the selection of proper maintenance concepts.

CBM+ is defined as the application and integration of processes, technologies, and knowledge-based capabilities to achieve target availability, reliability, and operation and support costs of DOD systems and components across their lifecycle . This development is further highlighted in next slide.

(US DOD INSTUCTION 4151.22)

$$\text{CBM+} = \text{CBM} + \text{IIOT} + \text{AI/ML}$$

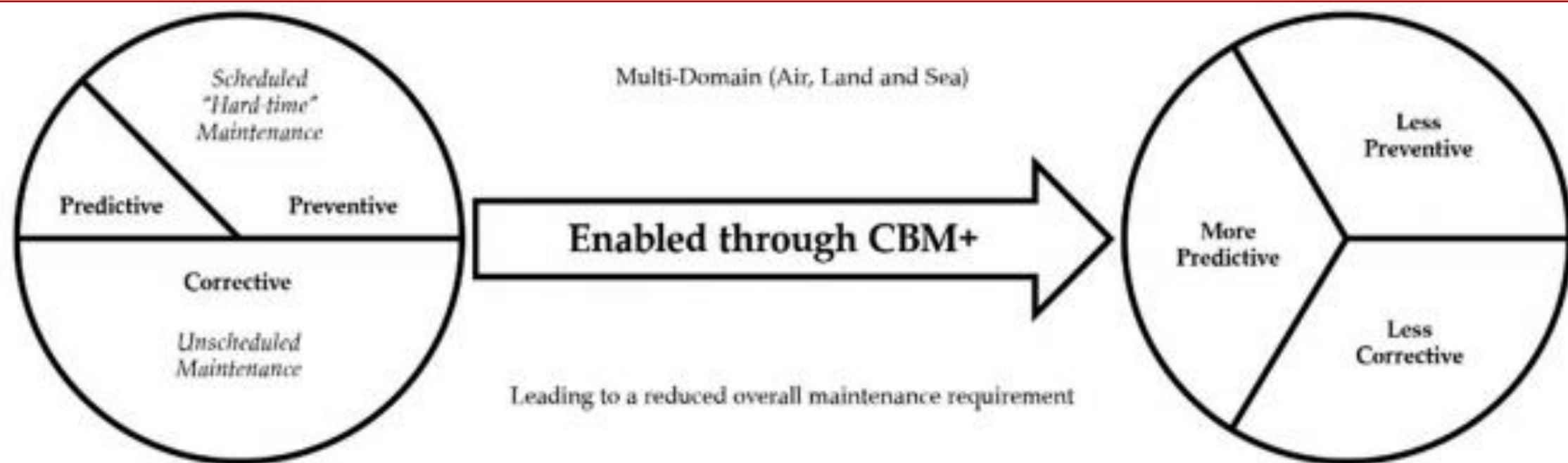
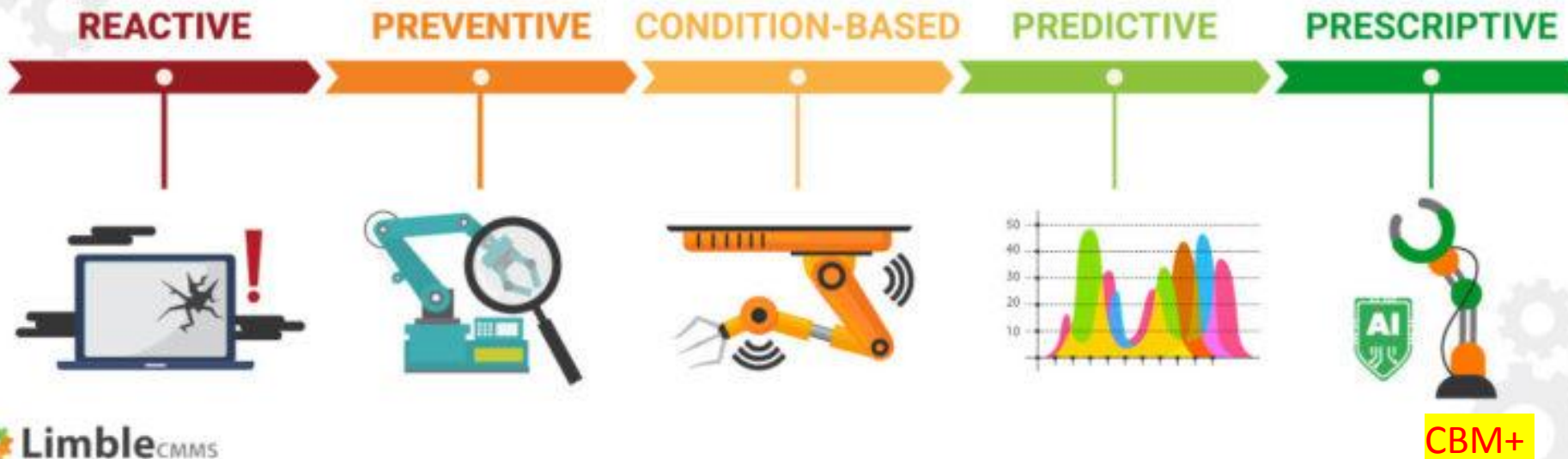


Figure 5. Representative illustration of the United States Department of Defense Maintenance Strategy Transition—"Enabled through CBM+" [80].

THE EVOLUTION OF MAINTENANCE STRATEGIES

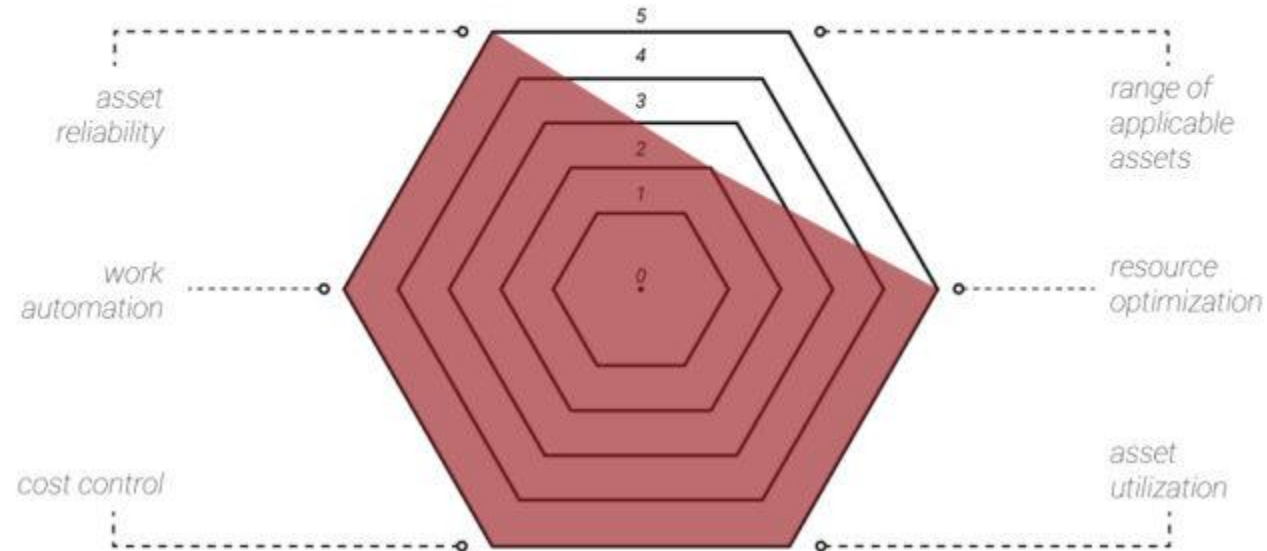


Automated AI based Prescriptive Maintenance

AI based machine health monitoring solutions offer real-time predictive information about the genuine health and performance of industrial assets. Right from the shop floor to the Top floor executives, one can offer actionable insights that significantly enhance maintenance of critical assets and manage failures effectively.

Advance early alerts & optimization of machine uptime with the latest predictive and prescriptive maintenance technology.

PRESCRIPTIVE MAINTENANCE STRATEGY BREAKDOWN



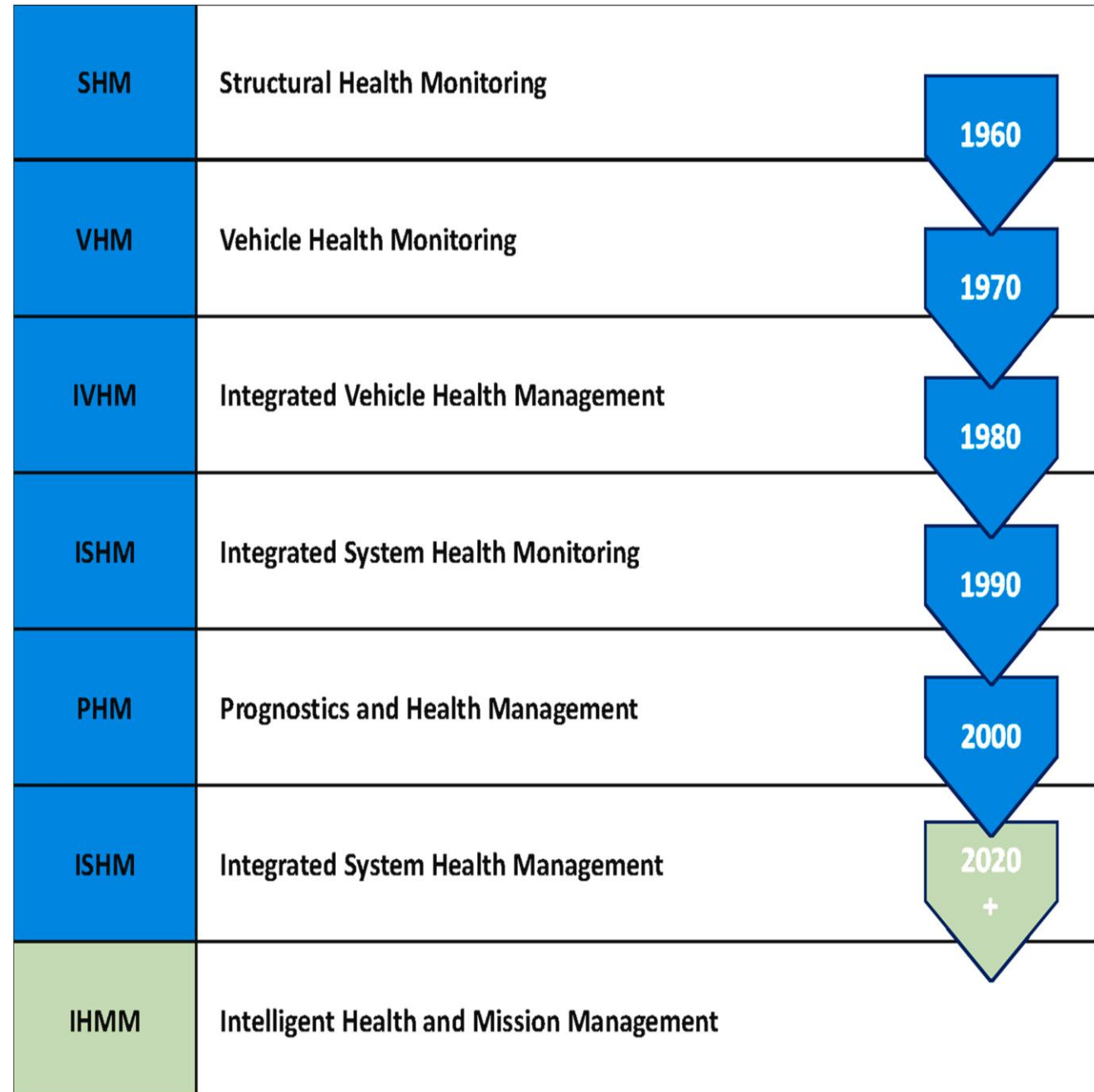
PROS

- 01 offers the highest level of automation
- 02 maximizes equipment uptime
- 03 offers the highest potential ROI
- 04 self-diagnoses and suggest potential solutions
- 05 helps to optimize your maintenance and production resources

CONS

- 01 requires big upfront investment into equipment and software
- 02 high training requirements
- 03 the most expensive and complex strategy to implement

‘Intelligent’ is used to emphasize the use of Artificial Intelligence (AI) that enables automated analysis of physical phenomena by imitating human reasoning, allowing the system elements to determine their health condition. In fact, in their roadmap for intelligent systems in aerospace, the Intelligent Systems Technical Committee (ISTC) of the American Institute of Aeronautics and Astronautics (AIAA)(2012) highlighted IISHM as a key enabling technology contributing to the improved operational efficiency, enhanced system performance and increased safety of future aerospace systems



ALIS: Maintenance Program F-35 (Rejected)



- The First Generation ALIS (Autonomic Logistics Information System).“system of systems” is an information technology infrastructure that captures and analyzes aircraft condition data from the F-35, supporting fleet operations, maintenance, fault-prediction and supply chain management. [Prime Contractor:Lockheed Martin](2012)
- A planned radio frequency data link capability that would enable the F-35 to transmit information to the ground while airborne—called the Prognostics and Health Management downlink—was also a part of it.
- ALIS performance was not satisfactory,Finally replaced by ODIN
- Operational Data Integrated Network, or ODIN, logistics information system finished their rollout to F-35 squadrons in January. (2022)

F-35 squadrons with ODIN (2022)

Operational Data Integrated Network

- This kind of high-speed diagnostic computer system performs a number of critical functions. One of those is **condition-based maintenance** wherein onboard sensors and computers monitor flight systems such as engine rotations or cooling functions.
- In addition, ODIN will examine the **component health** of on-board software and hardware throughout the aircraft such as avionics and other electronics. Part of the concept is to anticipate potential failures well before there is any kind of malfunction to both preserve the safety and survivability of the aircraft and also streamline the repair and maintenance process by getting ahead of the curve. Most of all, **a diagnostic or predictive computer system** of this kind can mitigate the risk of any kind of **in-flight malfunction** which could of course introduce substantial performance, functionality and even tactical complications and problems.
- The ODIN system, however, is not likely restricted to purely maintenance functions but also plays a vital role in aircraft information processing, management, and transmission. The F-35 is widely regarded as being at the **forefront of emerging AI systems**, meaning its **sensor fusion applications** began as mere concepts years ago.

What is IAHM as envisaged today?

- **Combination of technologies:** Onboard sensors, digitalization, data transmission, and data analysis, predictive analytics / Business analytics/ Prescriptive analytics and automation to provide information regarding aircraft system performance and structural condition in all operational/ critical envelopes in real time.
- **Creating such an aircraft architecture and databases with emphasis on** system design, analysis and optimization, information management, data flow and communication and control.
- **AI and ML will be key enablers in this transformation.** AI will be embedded into the digital systems used to design, manufacture, operate and maintain each systems.
- **Adaptive intelligence is the ability to learn from experience and use that knowledge to adapt to new situations.** Adaptive intelligence integrates all of the processes, knowledge, skills, and aptitudes that help you not only deal with change but take advantage of it and move forward
- **Use these result** to make aircraft airworthiness determinations, to provide economic efficiencies, to increase operational reliability, safety, security (block chains), maintainability while avoiding vulnerabilities such as Cyber attacks and malware intrusion.

This end-to-end digitalized automated process is known as Integrated Aircraft Health Management (IAHM)

Intelligent Health and Mission Management (IHMM)

Intelligent Health and Mission Management (IHMM), delves deeper into the utilization of on-line system health predictions to modify mission profiles to ensure safety and reliability, as well as efficiency through predictive integrity.

This concept is particularly important for Trusted Autonomous System (TAS) applications, where an accurate assessment of the current and future system state-of-health to make operational decisions (with or without human intervention) is integral to both flight safety and mission success.

IHMM systems introduce the capability of predicting degradation in the functional performance of subsystems, with sufficient time to dynamically identify which appropriate restorative or reconfiguration actions to take in order to ensure that the system can perform at an acceptable level of operational capability before the onset of a failure event.

IAHMS

Airframe Health
Management

Propulsion
Health
management

Aircraft Systems
Health
Management

Environmental
Hazard
Management

Validation &
Capability Testing

Simulation,
ground testing,
flight testing

environmental
testing

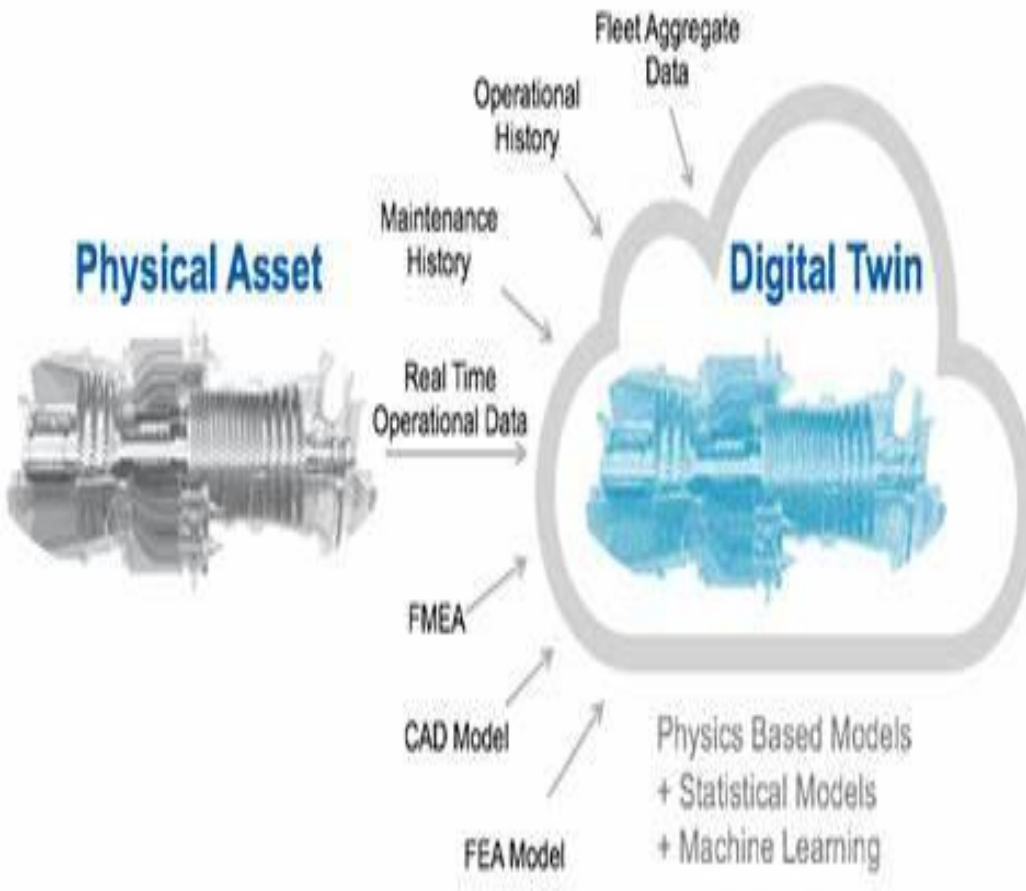
Software testing.

Opportunities and Challenges

This is first of its kind. How to utilize the enabling technology in a way that is both efficient and economical will be challenging. Common challenges that system designers and developers must overcome

- Practical implementation of algorithms for state-of-health estimation and the various steps involved in the prognostic processes, such as the choice of lead times, prediction of RUL/time to failure and overall prognostic methodology.
- The selection of health indicator features of subsystems or components is vital in any form of condition monitoring. Ideal health indicators would exhibit clear discrimination between the values associated with normal operating state and those associated with a given failure state.
- Data Security Challenges
- Vulnerable to Cyber attacks and malware intrusion
- Major challenge to overcome is to achieve certification for implementation in real-time applications.

Digital Twins and Condition Monitoring



- A digital twin is a digital replica of a physical entity
- The research is on **developing Digital Twins for optimizing maintenance and condition monitoring.**
- Allows the designer to optimize the system, reduce testing and certification costs.
- **Based on how different faults affect the system performance, strategies to aid faster diagnosis can be generated.**

DIGITAL TWIN- US Air Force Observations April 22

“Today’s digital twins talk to their physical counterparts—a bi-directional conversation exchanging sensor data, predictions, and updates”. “We leverage this dialogue to continuously and iteratively update our weapons systems. It’s a constantly improving feedback loop that we can apply throughout the life of a weapon.”

Sumpter cited **three reasons** for the Air Force to invest in digital twin technologies to apply to weapons system design, development, and sustainment: **technology convergence in the physical and digital realms, the promise of data sharing to improve weapon performance, and the need to adapt in the evolution of peer threats.**

“The power of the twin comes from turning data into information,” Sumter said. “A tremendous amount of data is generated for our weapons systems throughout their life cycle. This data is stored on servers and work stations housed in the secure areas of buildings—largely inaccessible and often effectively lost. Accessing and analyzing this data across a patchwork of formats and proprietary models can be time consuming...Digital twins change the paradigm [and] empower us to make intelligent sense of complex physical systems by making data available, connected, and organized—accessible through secure, cloud-enabled environments—and underpinned by standards and authoritative sources of truth.”

“Here at Eglin Air Force Base, we’re building a modern type of twin for the Air Force—a digital twin of Air Force weapons and assets,” James Sumpter, senior scientist and program manager for the Weapons Digital Enterprise/Digital Twin Lab of the Air Force Research Laboratory’s (AFRL) munitions directorate at Eglin AFB, Fla. told the AFRL Inspire summit on 28 April 22.

Contd.....

Digital twins may aid in weapons system sustainment through the use of condition-based monitoring and predictive maintenance algorithms, as continual monitoring of temperatures, shocks and vibrations on weapons systems would allow mechanics to fix the systems before they break. AFRL is also building next-generation digital twins to speed decision support for the planning of missions and their execution and for tactics optimization.

Digital Twins To Be New Hallmark for US Air Force Weapons
Systems

By Frank Wolfe | May 3, 2021

Structural Health Monitoring of Ships in US Navy

US Navy employs a modeling tool for structural health monitoring using nonlinear Kalman Filter methodologies such as the Extended Kalman Filter and the Ensemble Kalman Filter to identify damage within a structural model.

Through the observation of structural responses and the formulation of a Kalman Filter, it is possible to produce estimates of structural parameters related to damage, specifically changes to elastic modulus and changes in material density.

The results of this modeling tool were evaluated to quantify the time and length scales required for damage detection and were validated against a structural model generated in the MAESTRO Global Structural Analysis software suite.

Structural HM technologies

The SHM system architecture can be divided into two significant attributes as shown in.

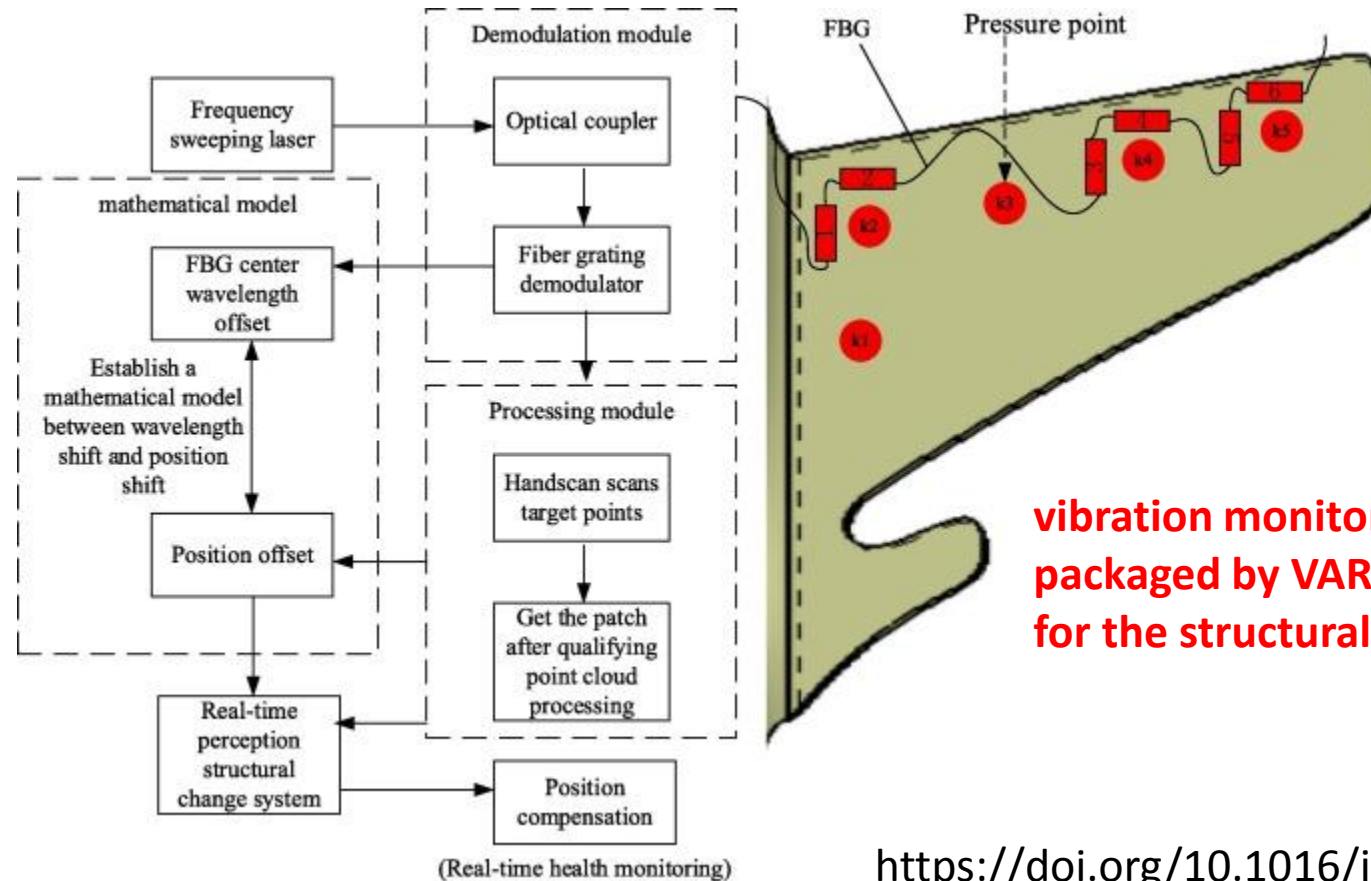
- **Physical architecture:** components and subsystems such as sensors, transducers, data acquisition (DAQ) systems, amplifier, wires, connectors and their interconnections
- **Functional architecture:** performance requirements such as reliability, probability of detection (POD), intended function (level of diagnosis) and damage size .

SHM intended that elementary functions can be divided into four levels (SAE International 2013)

- **Level 1 (Detecting the presence of damage):** This is the most elementary function of the system where it indicates whether damage exists or not with a pre-defined quality and to an acceptable probability (false positive and missed detection).
- **Level 2 (Detection of damage location):** Damage is not only detected but also localized with a prescribed accuracy (either zonal or exact coordinates depending on the required level of accuracy).
- **Level 3 (Detection of damage size):** This level of functionality is in addition to detection and localizing results in detecting the damage size to a set POD.
- **Level 4 (Detection of damage characteristics and the influence on residual strength):** The SHM system may be targeted towards characterizing the type of damage such as debonding, delamination, severity and single and multiple damages.

A structural health monitoring system for aircraft wings based on a fiber-optic grating sensing network

Vibration.
Strains
Deformations
using FBG sensors
can be efficiently
used for the
structural health
monitoring.



**vibration monitoring using FBG sensors
packaged by VARTM can be efficiently used
for the structural health monitoring.**

<https://doi.org/10.1016/j.rio.2023.100393>

Analytics at the Edge

Edge computing brings decision-making and intelligence as close to the process as possible.

lower latency
Scalability
Security
5G enhances capabilities
Software Defined Networks



Cyber Resilience of Condition Based Monitoring Capabilities (Ref US Navy 2020 document)

OBJECTIVE: To enabling cyber secure management of machinery monitoring that minimizes risk to information for maintenance actions.

The U.S. Navy is currently developing condition based monitoring concepts and technologies to provide diagnostic and prognostic capabilities using Machine Learning (ML) techniques. However, to the best of our knowledge, the applications of ML to formulate maintenance decisions on condition-based maintenance plus (CBM+) platform have not yet been explored

These concepts and technologies will enhance fleet performance and readiness through improved equipment availability, reliability, operation, and maintenance over their entire lifecycle. Advancement in low-power embedded sensors, microcontrollers, and wireless technologies has fostered development of new sensor nodes and computational processes that enable use of CBM+ strategies. These CBM+ platforms represent a growing class of cyber-physical systems (CPS) that are being considered for integration on existing and future Navy vessels.

These sensor nodes have the potential to serve as targets for cybersecurity attacks or be susceptible to corruption through accidental or malicious events.

A successful technology development and transition will result in a **secure CBM+ sensor node that can minimize human intervention and reduce the number of machinery overhauls, shorten time spent in depot for repairs, and optimize maintenance logistics by at least 50%.**

Several data and model-based techniques

	noise analysis	transform (CWT),
Signal processing-based techniques	radio-frequency (RF) analysis	discrete wavelet transform (DWT),
image processing based techniques	infrared analysis	Kalman filtering,
data fusion techniques	current and voltage analysis	Wiener filtering,
data mining techniques	electromagnetic field analysis	Empirical mode decomposition (EMD)
and expert system techniques	oil analysis	, variational mode decomposition (VMD),
chemical analysis,	pressure analysis	and singular value decomposition (SVD)
electrical analysis,	ultrasound analysis	Big data: How to pick useful diagnostic information from different sensors quickly.
mechanical analysis,	and sound and acoustic emission analysis	
temperature analysis	data denoising and filtering.	
vibration analysis	nonlinear and nonstationary signals analysis	
	, wavelet transform (WT),	
	continuous wavelet	

Secure scalable Blockchain Ecosystem for End to End Data Exchange

(SAN FRANCISCO, May 11, 2023)

US DOD claims a major milestone to have validated a Block Chain software for the DOD application through the Air Force Research Laboratory (AFRL) as a scalable, secure and defense approved Blockchain application demonstration.

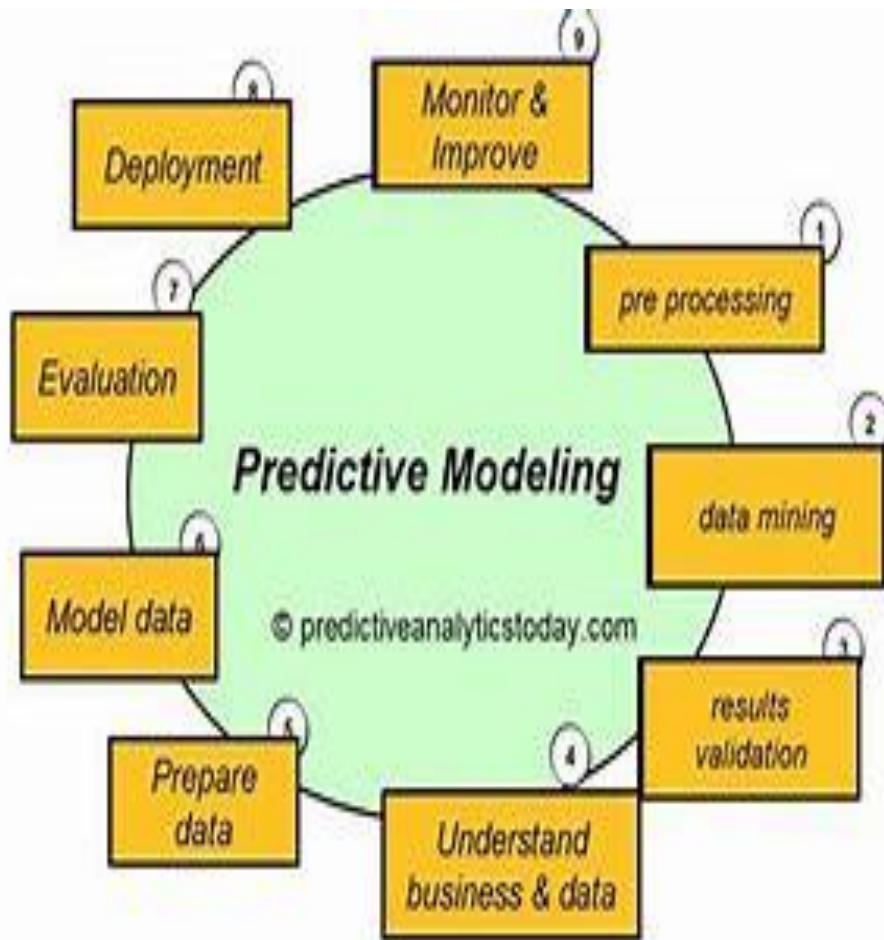
Constellation Network ,a privately funded company has a Blockchain ecosystem with the development of Hypergraph Transfer Protocol (HGTP).

HGTP provides Web3 developers a comprehensive network to cryptographically secure, validate, and process data for any digital application.

Constellation Network has productized Web3 development tools, such as their Euclid SDK, allowing anyone to build Blockchain networks for big data, creating trust and transparency around data collection, validation, and transacting.

HTTP is the foundation to the World Wide Web, HGTP contains the rules that shape the way Blockchains seamlessly and securely communicate sensitive data with one another.

Virtual Reality and Predictive Analytics

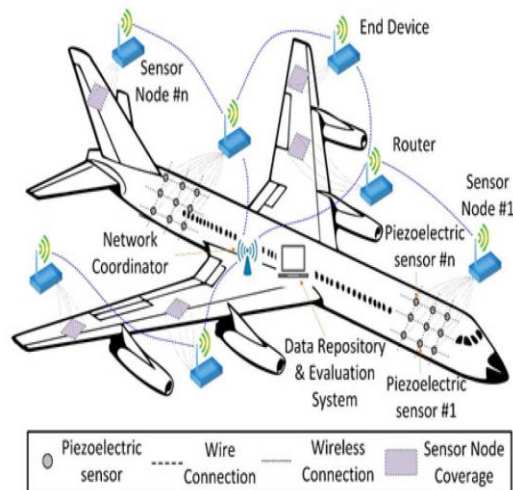


- Predictive analytics combined with virtual reality (VR) technology for the U.S. Army Aviation program.
- Applied to view the effects of fault progression in the wear of gears and how it affects the health of the gears showcasing an Apache tail rotor drive train intermediate gearbox .
- It gives hopes to provide the manufacturing industry a methodology for producing zero-defect products.
- Upcoming Metaverse Technology deals with this

Source : Predictive Maintenance Centre&Visual Art and Design and Research Univ of South Carolina, Clemson University, the Fraunhofer Institute, and the South Carolina Department of Commerce.

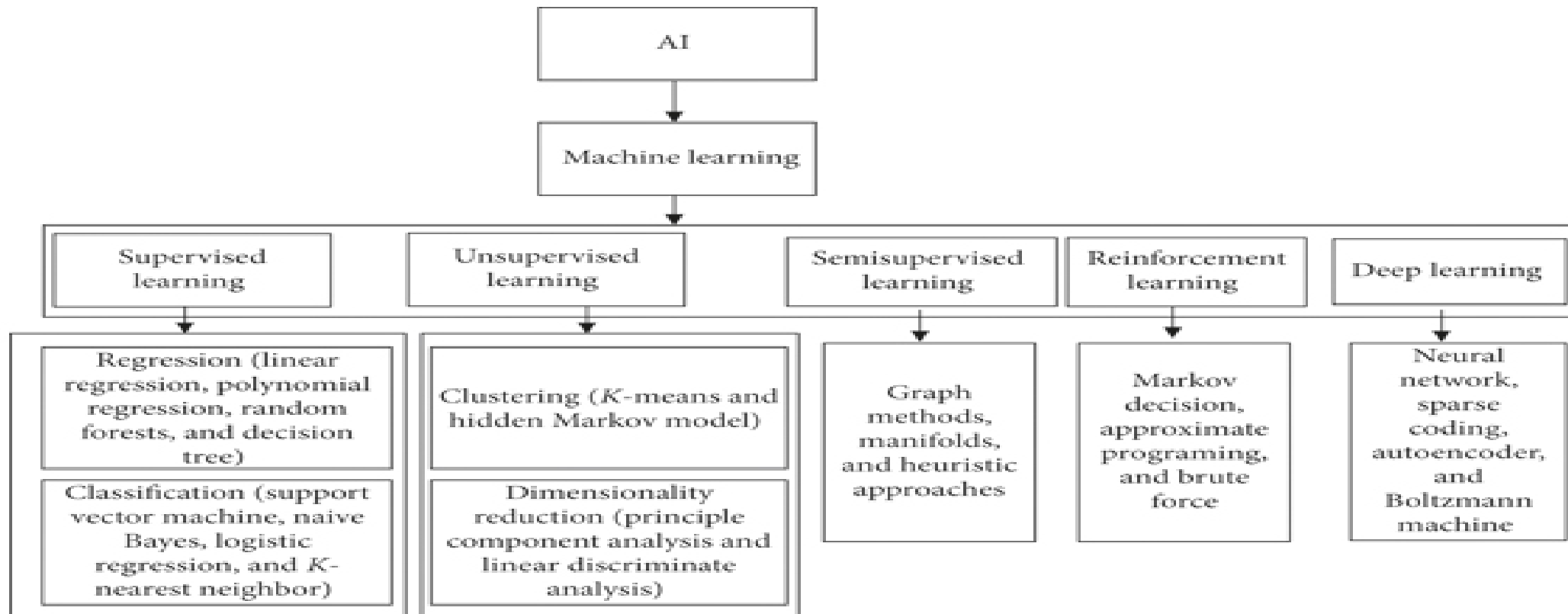
Condition Monitoring For Aircraft Monitoring

Aircraft Health Monitoring System Market Size
(2015-2018)



- Aircraft Condition Monitoring System (ACMS) /Aircraft Health Monitoring Systems (AHMS). Essential to improve aircraft performance and optimize their service lifetimes. **Data is collected Wirelessly. the units made for Airbus and Boeing can transmit flight data via 4G/ 5G.**
- They use real-time data captured through various sensors integrated on aircraft parts to enhance reliability and safety of the aircraft.
- They can **optimize MRO costs by replacing cost-intensive and invasive maintenance work with non-invasive inspections and testing that report on the aircrafts' condition and minimize aircraft downtime**

AI methods used in CM and FDD for rotating machinery.



Future Tech Developments in next 5 years:

Smart World with increased fusion of Physical Digital Experiences

Neuromorphic Computing & Devices

Metaverse

Human-centred AI

Self-Supervised Learning

Edge AI

The time has arrived for us to develop and embrace the latest autonomic AI/ML technology and that will let machines / systems analyse their own data from sensors to identify when they require maintenance or new components.

Thank You