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NSRP National Shipbuilding Research Program

Predictive Maintenance for Critical Assets in Shipbuilding

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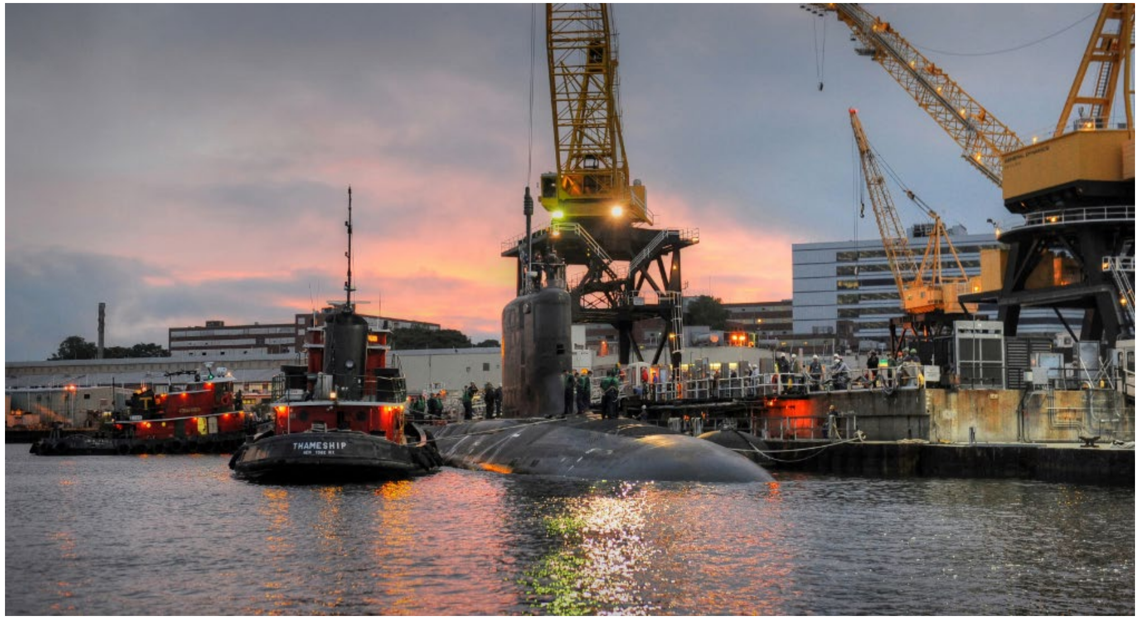
Today's Presentation

- Issue
- Objectives & Goal
- PM II IIOT:
  - Advanced Monitoring Concepts
  - Edge Devices
  - Data Modeling / Anomaly Detection
  - Anomaly Detection in Health Monitoring
- Project Approach
- Project Status
- Next Steps
- Acknowledgements
- Questions

Issue

- GDEB critical path manufacturing assets experience catastrophic failure despite Preventative (PM) and conventional Predictive (PdM) maintenance programs.
  - 1st Tier Impact: Unnecessary costs for asset repair, lost production time, and workarounds.
  - 2nd Tier Impact: Schedule slip for weapon system delivery or refurbishment.
- Initial solution: Manually interrogated diagnostic monitoring systems transitioned under "Diagnostic Monitoring of Equipment and Capacity Planning" proved to:
  - Avoid unexpected and unnecessarily extended downtimes
  - Circumvent catastrophic failures
  - Eliminate replacement of complete systems and subsystems due to failures affecting other parts/systems
- Continued issue: Not all critical path equipment is amenable to manual monitoring of health (conventional PdM) due to access or confined space issues.
- Advanced solution: Supplement conventional PdM with advanced industrial internet of things (IIoT) technology to automatically communicate impending faults/failures.
- Impact: Timely delivery of VCS and CLB platforms.



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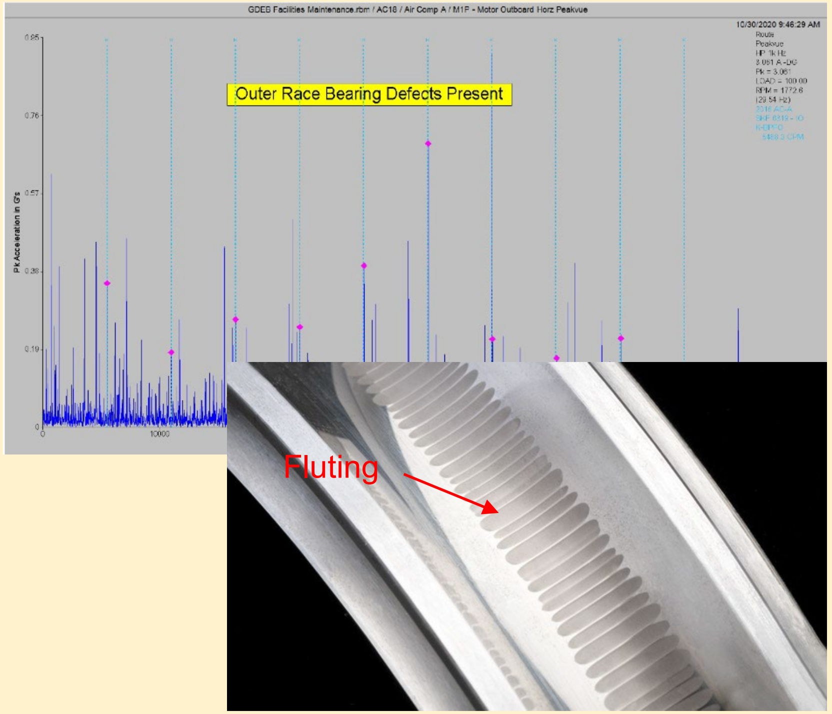
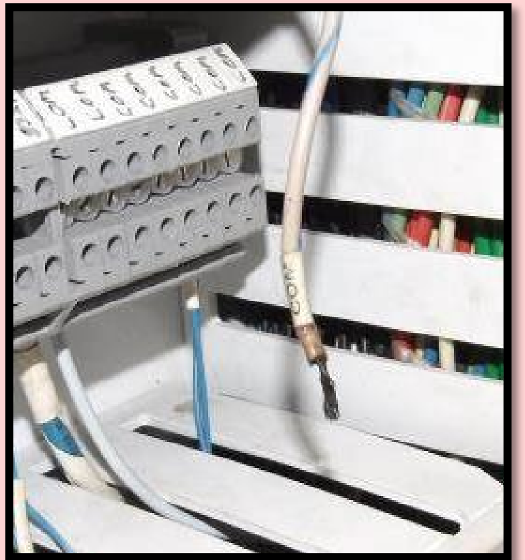
Issue: Manual Monitoring Case Studies

- **Vibration analysis** detected a severe bearing fault in a compressor motor due to energy leakage.
- Corrective Action: Implement Inductive Absorbers that reduce the high frequency components and eliminate bearing damage.
- EROM Savings: $48K ($60K replacement vs. $12K repair

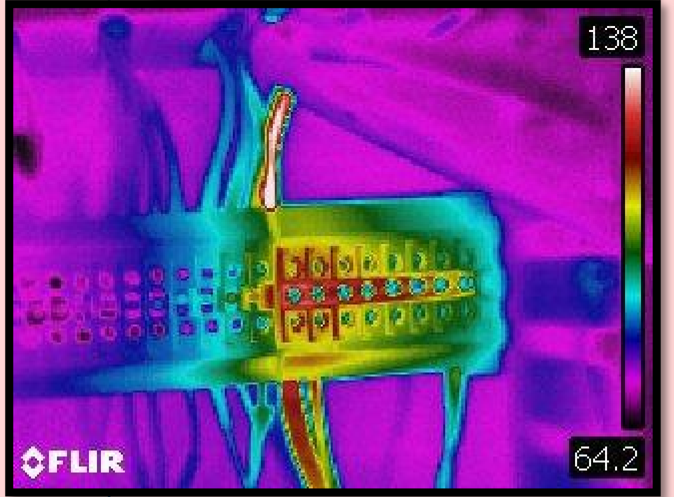


Equipment	Moisture	Viscosity	Total Acid Number
Standards	**< 0.05 %**	**41 – 50 @ 40 C**	**< 1**
Dewatering Pump Motor 1 Top	< 0.01 %	54.2	2.2
Dewatering Pump Motor 1 Bottom	< 0.01 %	40.5	2.2
Standards	**< 0.05 %**	**16.3 - 21.9 @ 100 C**	**< 1**
Dewatering Pump Motor 2 Top	< 0.01 %	25.9	13.3
Dewatering Pump Motor 2 Bottom	< 0.01 %	25.3	12.4

- Fluid analysis detected out of specification motor lubrication oil.
- Corrective Action: Replace lubrication oil immediately
- EROM Savings: $49.8K for motor replacement

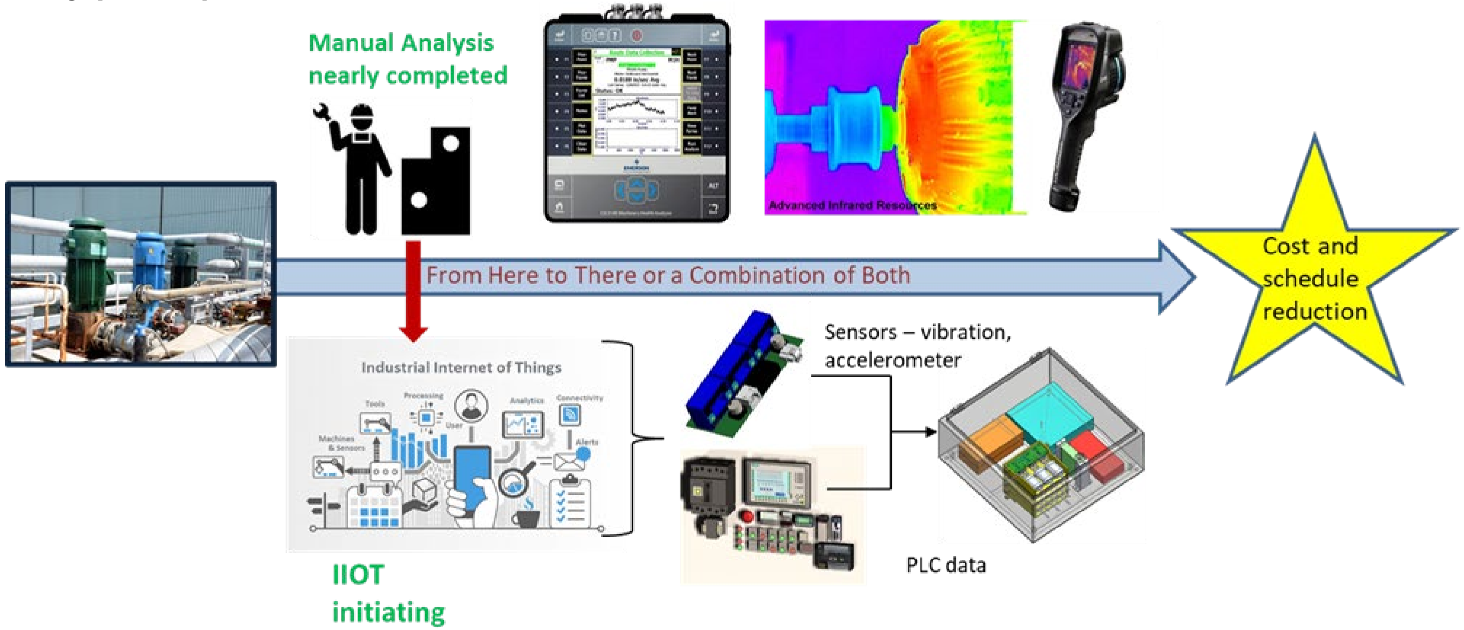


- **Infrared analysis** (thermography) detected excess heat generated from control system panel wire for a hull fabrication fixture. Wire was melted and oxidized.
- Corrective Action: Strip, clean, and re-attach the wire.
- EROM Savings: $45K cost avoidance of panel loss.



Objectives and Goal

- Identify critical path equipment for implementing IIOT technologies
  - Enables expanse of asset management and predictive maintenance of GDEB critical path manufacturing equipment for VCS and CLB.
- Provide machinery health predictions for maintenance and production planning of previously inaccessible critical path equipment.
  - Wireless sensor technologies and edge computing devices
- Prototype optimum combination for GDEB VCS and CLB manufacturing



Predictive Maintenance using hand-held thermography and vibration analysis equipment, supported by oil analysis

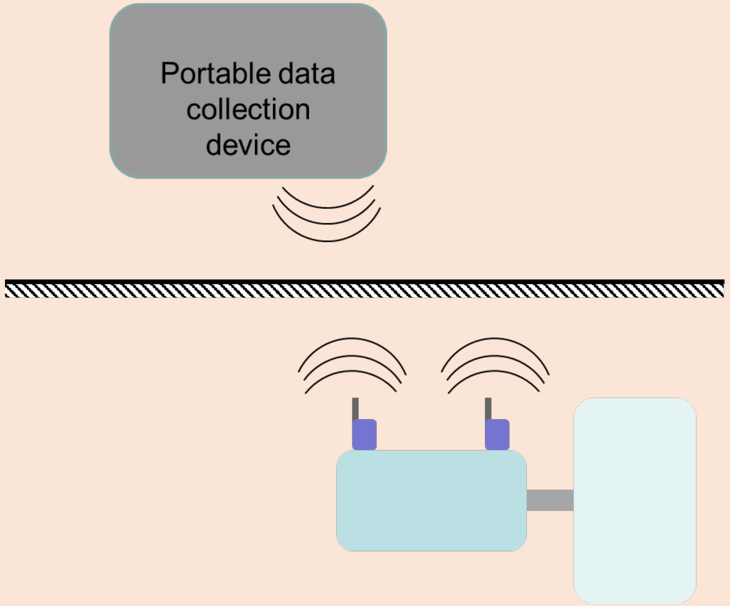
Predictive Maintenance using PLC data w/ ML & high frequency data w/physics-based techniques offers real time QC assessment

- Goal: Monitor all critical path VCS/CLB manufacturing equipment to reduce costs and schedule disruption.

PMII IIOT: Advanced Monitoring Concepts

(1) Targeted wireless condition sensing

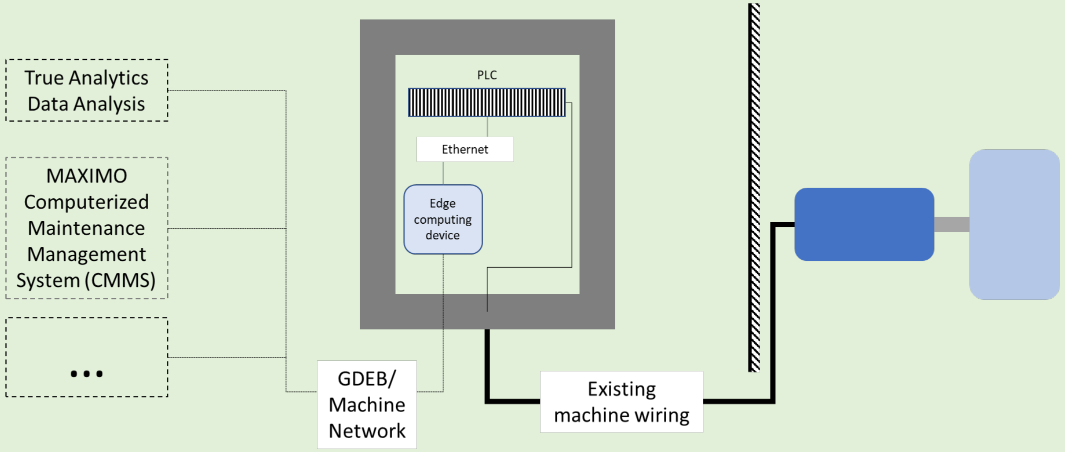
Maintenance technicians still walk routes to collect data, but rather than mounting their sensor to the asset at each point, they wirelessly collect data from permanently installed sensors.



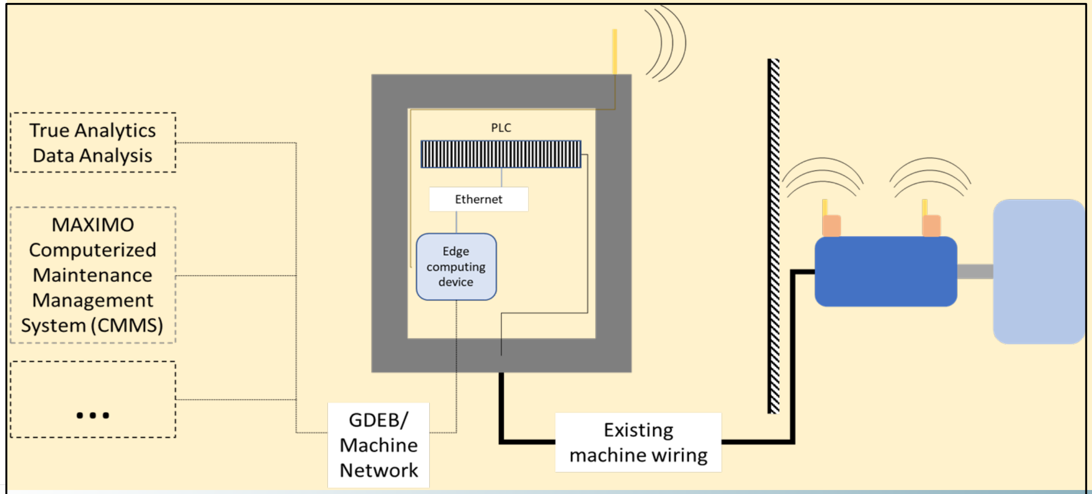
Technician can collect data from afar – **no more climbing**

- Onto roofs
- Onto cranes
- Into below-ground pits/tank watch areas

(2) Collection from existing health adjacent sensors



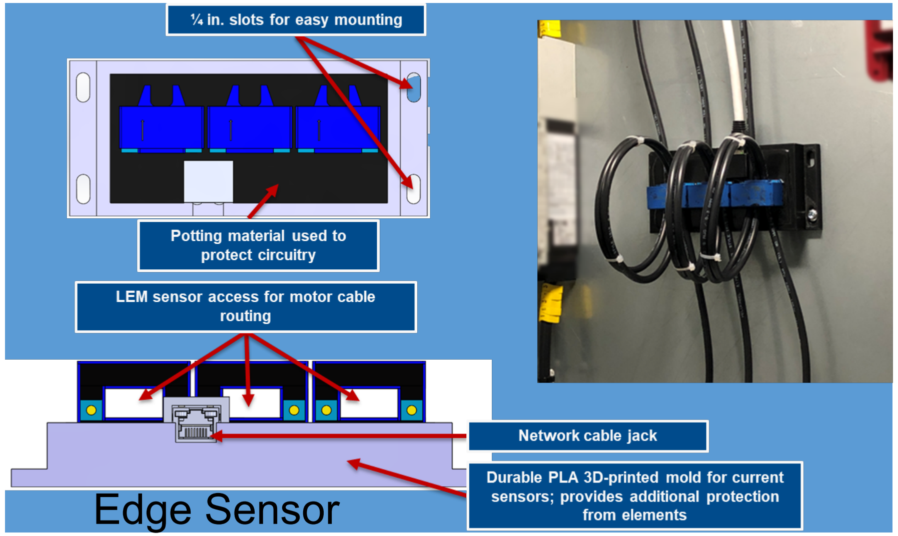
Take data from PLC and communicates results to enterprise level information systems such as data analytics tool (True Analytics or Viannix) or CMMS. An additional edge computing device (as compared to targeted wireless condition sensing), may be required for pre-processing.



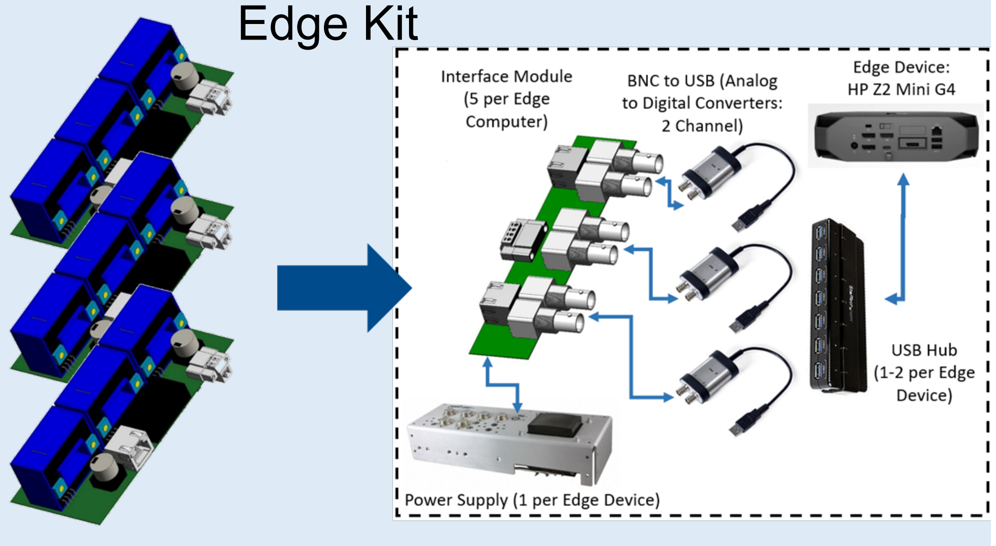
(3) Integrated wireless condition sensing and existing health adjacent sensors

Combination of 1 & 2 but uses persistent, autonomous data collection system.

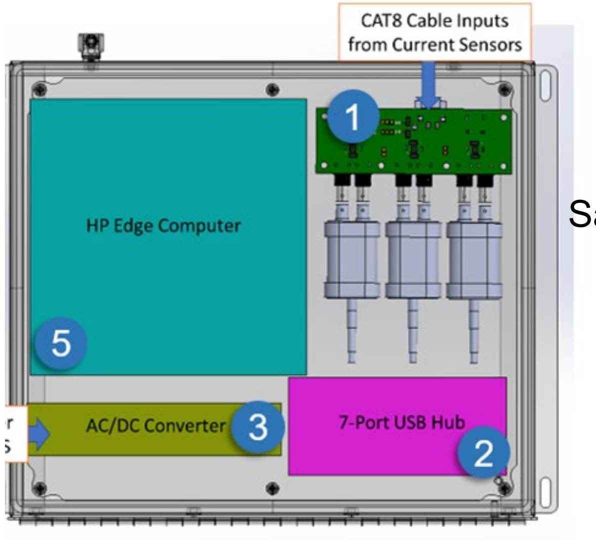
PM II IIOT: Edge Devices



Multiple Edge Sensors connected in a kit



Edge computing device is capable of collecting data from the existing PLC and wirelessly collected asset health data using the developed sensors. Allows for Multiple Data Streams and Processing on a Single Device



Sample Output Data From Bearings

Modeling techniques used to indicate bearing failure and send to User Interface Display

PM II IIOT: Data Modeling / Anomaly Detection

- Outlier detection relies on building a model of expected behavior and finding aberrations
- Humans do it intuitively all the time
- Multiple methods exist to automate identification of outliers
- Methods based upon:
  - Visual inspection - Interactive plotting/dashboarding
  - Distribution statistics - Parametric modeling/statistical process control
  - Proximity approaches – Clustering/unsupervised models
  - Time series models - Matrix Profiling, ARIMA modeling
  - Optimized data compression - Autoencoders

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PM II IIOT: Anomaly Detection in Health Monitoring

- Model building
  - Perform anomaly detection– each observation is classified as either “inlier” or “outlier”
  - Subjectively score the anomaly detector by comparing periods of anomaly detection to noted periods of machinery malfunction/aberrant behavior
- Model application
  - Newly captured data points are classified as either “inlier” or “outlier”
  - After identifying a sufficient number of outliers in a certain period of time, notify maintenance personnel of potential upcoming issues
    - Compare new, outlying sensor values to historical outlying sensor values with recorded maintenance/machinery faults, identify most similar fault and likely required corrective action

Project Approach

Phase 1: State Assessment and Technology Identification and Selection

- Review/Update Current State Assessment with RCM Analysis — ECD Q2FY23
  - Conduct Failure Modes and Effects Analysis (FMEA) — GDEB Completed Q1FY23
  - Identify IIoT Requirements — GDEB Completed Q1FY23
  - Review/Update Capacity Planning Integration Plan — ECD Q2FY23
  - Establish Unclassified Information System — ECD Q2FY23
- Perform Vendor Assessment/Selection — Completed Q2FY21
  - Identify IIOT Solutions — Completed Q1FY23
  - Select or Develop IIOT Technology — ECD Q2FY223
- Conduct Business Case Analysis — ECD Q2FY23
  - Conduct Cost Analysis — ECD Q2FY23
  - Conduct Historical Time Study — ECD Q2FY23
  - Conduct Business Analysis — ECD Q2FY23
  - Perform ROI Refinement — ECD Q3FY23
- ONR Go/No-Go Decision #1 — ECD Q3FY23
  - Go/No Briefing — ECD Q3FY23
  - Interim Report — ECD Q3FY23

Project Approach

- Phase 2: IIoT Technology Development, Pilot, and Verification
  - Secure System Integration Development — ECD Q3FY24
    - Select or Develop Final Design for Sensor Integration — ECD Q3FY23
    - Develop Final Architecture for Predictive Maintenance and Capacity Planning Integration — ECD Q3FY23
    - Procure IIOT Solution Components — ECD Q2FY23
    - Review Needs for Customer User Interface — ECD Q3FY23
  - Perform Pilot Program — ECD Q2FY24
    - Install Sensors and Selected IIoT Technology — ECD Q3FY23
    - Conduct Initial System Test — ECD Q3FY23
    - Perform IIoT Pilot Test — ECD Q2FY24
    - Execute IIoT Pilot Training — ECD Q2FY24
  - Conduct IIOT Demonstration — ECD Q2FY24
    - Plan Demonstration — ECD Q2FY24
    - Create GDEB Implementation Plan — ECD Q2FY24
    - Execute IIOT Demonstration — ECD Q2FY24
  - Conduct Cost Benefit Analysis Update — ECD Q2FY24
    - Conduct Cost Analysis — ECD Q2FY24
    - Conduct Business Analysis — ECD Q2FY24
    - Perform ROI Refinement — ECD Q2FY24

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Project Status

- Conducted Failure Modes and Effects Analysis (FMEA) on 10 critical assets
  - Cranes, Presses, Formers, Fixtures, Pumps, HVAC units, compressors, heaters/chillers
  - Identified key locations for monitoring: hydraulics, drive systems, clamps, lifting systems, pumps, motors, compressors

Failure Mode	Symptoms/Effects	Sensors	Sensor Component	Item Qty	Sensor Component Quantity	Vibration Measurement Location Qty	Oil Measurement Location Qty	Thermography Measurement Location Qty	Motor Signature Analysis Qty	Pressure Measurement Location Qty	Comment
Electrical wire failure	Electrical arcing through failed insulation will lead to corona discharge	Ultrasonic sensors	Wires	1	1						
	Increased heat from increased electrical resistance within wire	Thermography	Wires	1	1			16			
	Increased current draw when lifting standardized load	Current transducers	Wires	16	16				16		
Receiving shoe failure	Increased heat due to increased electrical resistance of shoe	Thermography	Receiving shoes	8	1			8			
Motor Bearing Failure	Degraded Rotational Performance	Accelerometer	Motor Bearings	6	2	12					
	Change in the Characteristic Bearing Vibration Signature	Accelerometer	Motor Bearings	6	0						
	Lubrication Contamination due to Bearing Material Wear	Lube Contamination	Oil Sample	6	0						
	Increased Motor Temperature	Thermography	Motor Housing	6	1			6			
Motor Internal Failure	Change in the Voltage/Current of the Motor	Voltage/Current	Motor Power	3	3				9		
Gantry wheel bearing failur	Degraded Rotational Performance	Accelerometer	Gantry Wheel Bearings	4	2	8					
	Change in characteristic Bearing vibration signature	Accelerometer	Gantry Wheel Bearings	4	0						
	Lubrication Contamination due to Bearing Material Wear	Lube Contamination	Gantry wheel bearings oil samples	4	0						
	Increased bearing temperature	Thermography	Gantry Wheel Bearings	4	1			4			
Gantry Geartrain failure	Degraded Rotational Performance	Accelerometer	Geartrain bearings	6	2	12					
	Change in characteristic Bearing vibration signature	Accelerometer	Geartrain bearings	6	0						
	Lubrication contmination	Lube Contamination	Geartrain oil sump	3	1		3				
					Accelerometer Locations =	32					
					Oil Locations =		3				
					Thermography Locations =			34			
					Motor Signature Analysis =				25		
					Pressure Sensor Locations =					0	

Sample FMEA

Project Status

- Determined IIoT operational requirements and evaluated high frequency collection systems
  - Identified 5 systems capable of collecting triggered/irregular high speed data from wireless accelerometers and wireless current transducers
    - Erbessd
    - Emerson
    - Petasense
    - KCF
    - PCB
  - Identified standard frequency data collection system
    - Need system that is already in use that accepts/aggregates/presents standard data sets
    - Viannix – installed at QP for real-time location monitoring
    - True Analytics – being explored at QP; gathering more information
    - Both are IT/Cyber approved = paths of least resistance for data visualization
  - Requires Federal Information Processing Standards [FIPS] 140-2/3 compliance

Project Status

- Developed decision matrix with weighted selection criteria (right) for sensing system
  - GDEB and ARL agreed upon scoring criteria and associated weights
  - Deal breaker scores makes entire solution non-viable if not met
    - Must be non-cloud based
    - Must meet FIPS 140-2/3
  - Erbessd was only system able to meet deal breaker criteria.
- Data visualization tool is still to be determined in cooperation with GDEB IT
  - Focus on more mature tools (Viannix or True Analytics)
  - Working with GDEB IT lead

Decision Matrix Criteria for Selection

Field	Weight	Deal breaker score	Scoring Values
FIPS 140-2/3 encryption		N	Y/N
Timeseries data transmission	5	N	Y/N
Ability to Maintain Organically (y or n)	4		Y/N
System capable of meeting NIST 800-171	5	N	Y/N
Locally hosted (vs. public cloud hosted)	5	N	Y/N
Server software compatible with Windows/Linux	5	N	Y/N
Client software is windows accepting	2	N	Y/N
Docker usage	5	N	Y/N
US Based Vendor	5	N	Y/N
1 year warranty on hardware	3		Y/N
Data Collection Rates Commensurate with Analysis	5		1 to 10
Ease of Expansion to Other Assets	2		1 to 10
Remote sensor component survivability	5	0	1 to 10
System scaling and capacity	4	0	1 to 10
Hardware cost Ranking	4		1 to 10
Flexible data collection methods (triggered, etc.)	3		1 to 10
Ease of collecting non-vibration signals	3		1 to 10
Battery availability	4		1 to 10
Battery life	3	0	1 to 10
Remote sensing installation ease	2		1 to 10
IT/Cyber Approval Timeframe Ranking	1		1 to 10
Integration with existing collection technology (PLC captured data, edge device captured data)	3		1 to 10
Data storage scheme authorized user accessible	4	0	1 to 10
Software cost Ranking	4		1 to 10
Software has built-in fault classification	1		1 to 10
Native balancing analysis	1		1 to 10
Ease of Use/ Understanding Output	1		1 to 10
Built in trend/change point detection	2		1 to 10
User Support (support after installation)	2		1 to 10
Willingness to Work with ARL/GDEB on Pilot (gratis)	3		1 to 10
Recurring costs	4		1 to 10

Project Status

- ARL cybersecurity approved Erbessd system use at PSU/ARL facilities
- Demonstrated the Erbessd system outside GDEB facilities (Q4FY22 and Q1FY23)
  - ERBESSD VP conducted demonstration and answered GDEB AET and Maintenance questions
    - GDEB AET and Maintenance are jointly generating an RFQ for the additional sensors
      - ❑ Considering type/quantity of gateways and sensors required and software package that best suits GDEB needs after pilot use/demonstration
- Establishing unclassified information system
  - GDEB approved NUC use with manually collected data (Diagnostic Monitoring)
    - Multiple courses of action use manual collection of data (e.g., manual and wireless)
    - Approval needed for NUC, as customized data visualization solution likely requires NUC use
    - Enables predictive maintenance data movement on network between QP and Groton – needed for data visualization
  - GDEB IT is establishing secure data network, so NUC used in the interim for the PM II
    - Estimated completion of secure data network in early Q2FY24

Project Status

- Updating Capacity Planning Integration Plan
  - Discussed predictive maintenance equipment integration and capacity planning with GDEB QP Spatial Planning personnel (Q1FY23)
    - Found that full software demonstration may not be possible due to integration point difficulties
  - GDEB conducted CMMS demonstration for PSU/ARL (Q2FY23)
    - Scheduling preventative maintenance and repairs (e.g., repair tickets, facility service requests, and temporary service requests like temporary lighting)
    - Storing data within cloud-based system (no backend database ties); makes integration with capacity planning tools difficult
      - ❑ Investigating PM data input into capacity planning tools using reporting functions in CMMS; will not be real-time
      - ❑ Unsure if data from capacity planning tools can be fed into CMMS (cloud concerns)
    - PM dates listed in CMMS provides date work order appears in queue, not dates work will be performed. PM dates are determined after meeting with production team.
    - Developed draft integration plan to assist with further discussions with GDEB

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Project Status

- Conducting Business Case
  - Developed Courses of Action (COA) spreadsheet and questionnaire
    - Obtaining data from IIOT vendors and GDEB on manufacturing assets for the CBA
    - Gathering cost impact data to implement PM II - IIOT
  - Identifying necessary data for historical time study required for COA review
    - Obtaining FY22 data on selected assets and working to obtain older data
    - Identified additional assets in CLB facility; included another crane and 3 pumps
  - Identified possible COAs that need validated with cost information
    1. Status quo: Continue with manual, route based health data collection and analysis established during "Diagnostic Monitoring" program
    2. Update the collection of health data: Implement advanced, wireless, semi-autonomous health data (accelerometer) collection systems
    3. Collect "health-adjacent" data: Implement systems that collect sensor feeds already consumed by equipment PLC/control systems
    4. Mix-and-match from 1-3
       - COAs 1-3 are not exclusive approaches
       - The "mix" can (and should) be customized to the machine

Next Steps

- Near-Term Milestones to be Addressed
  - Complete Historical Time Study (GDEB)
  - Select course of action to proceed to in Phase 2
  - Conduct Phase 2 Go/No-Go Decision
- Technical Progress to be Accomplished
  - Collect maintenance records/costs for candidate assets
  - Provide GDEB IT with sufficient data to draft security plan to ensure compliance with GDEB IT and cybersecurity policies
  - Develop training plan for data collectors/analysts
  - Develop Draft *Capacity Planning Integration Plan*
- Risk Reduction Items to be Addressed
  - Working with GDEB IT and Cybersecurity early and often to address any potential constraints on IIOT software or hardware use at GDEB

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Acknowledgements

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  - Mr. Mike Magee – EB AET
  - Mr. Dave Fuller – EB Facilities Tech
  - Ms. Kristie Woodward – EB Facilities Tech
  - Mr. Erin Brewster – QP Spatial Planning
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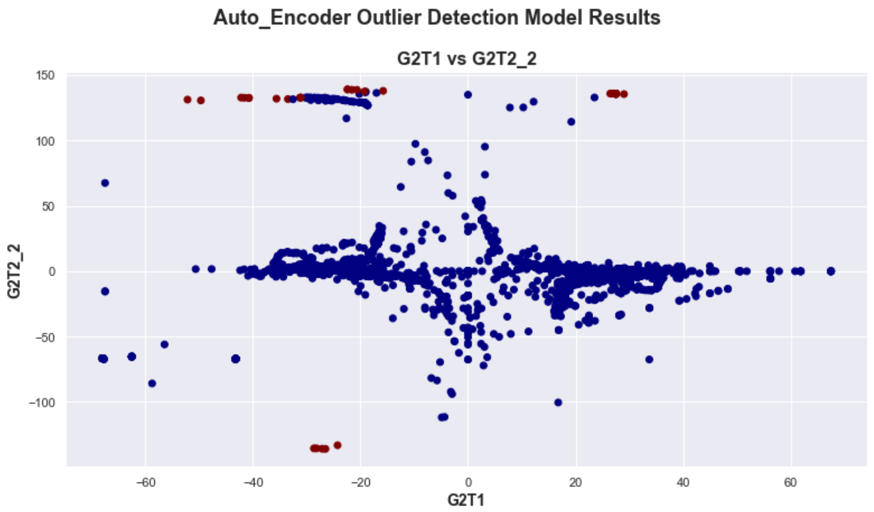
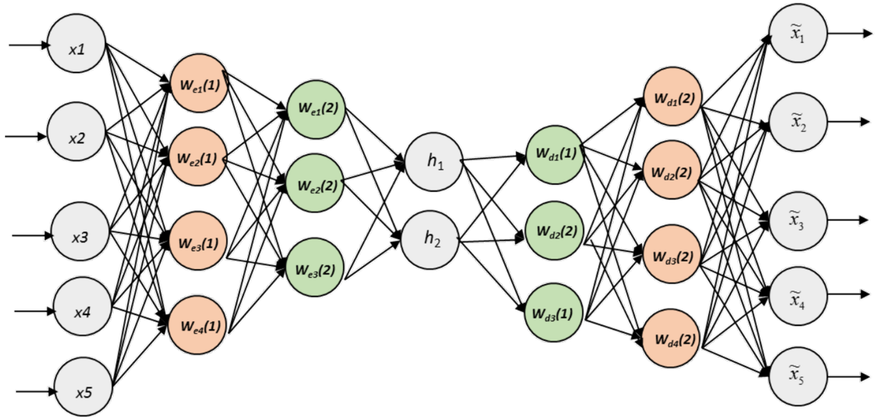
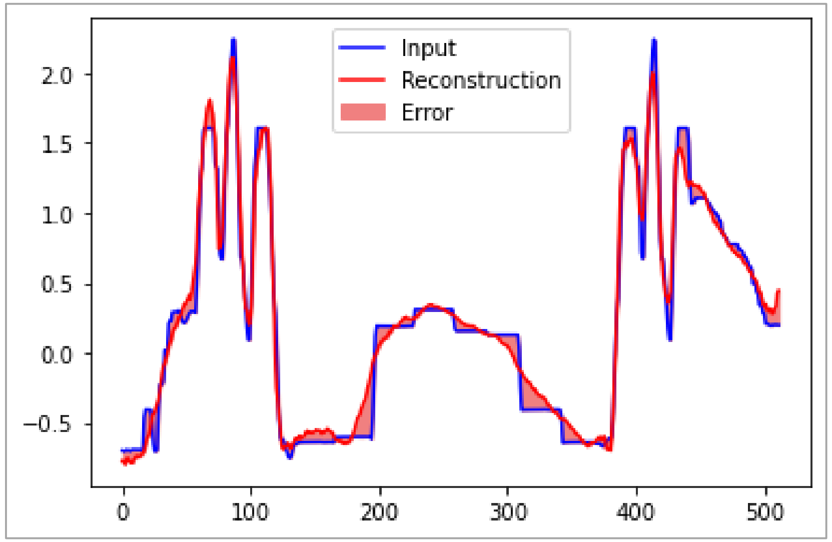
Modeling Techniques - Autoencoders

- Dimensionality Reduction through Encoding
- Neural Net Trained to reconstruct input features
- Data reconstruction fails when asked to reconstruct anomalous sensor values
- Anomalies Scores are Based on the reconstruction error – how different is the autoencoder's prediction from the input?

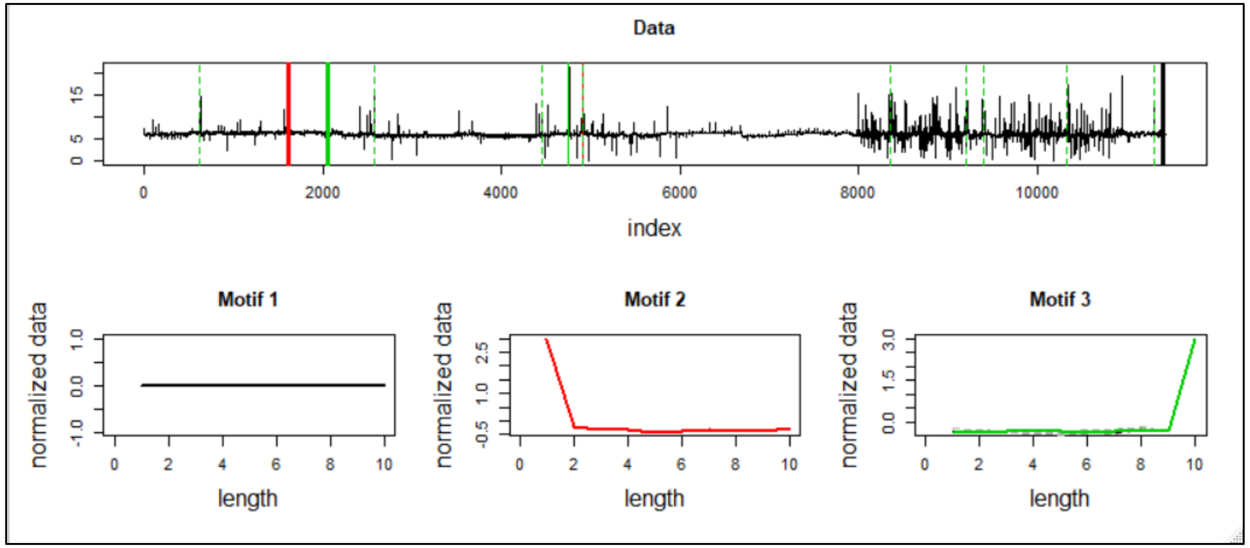




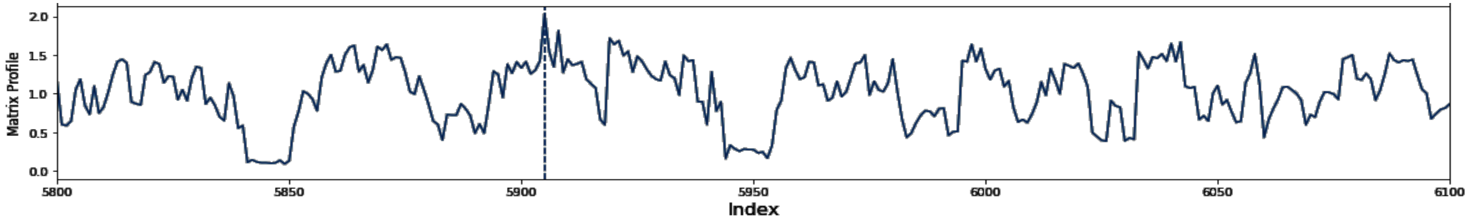


Modeling Techniques – Matrix Profile

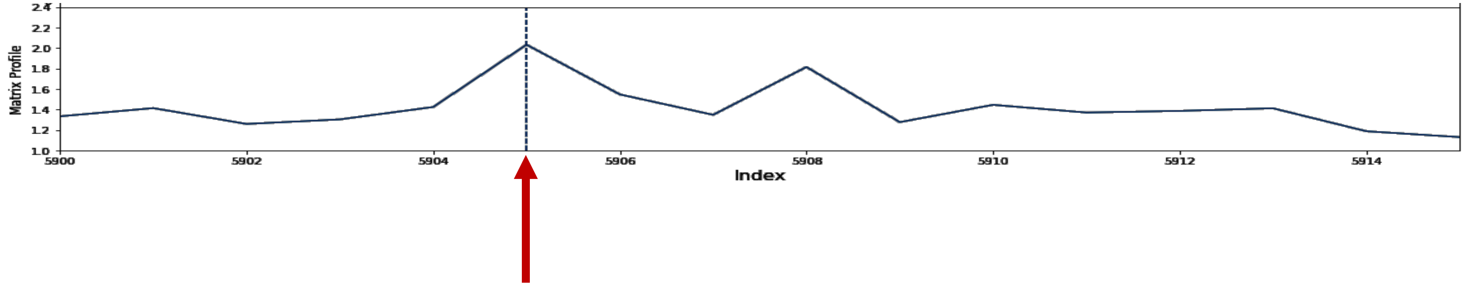
- Iteratively compare each “section” of sensor values to all others in the time region, and record a measure of how similar (on average) the entire series is to each window



- Sections which are repeated the most: motifs

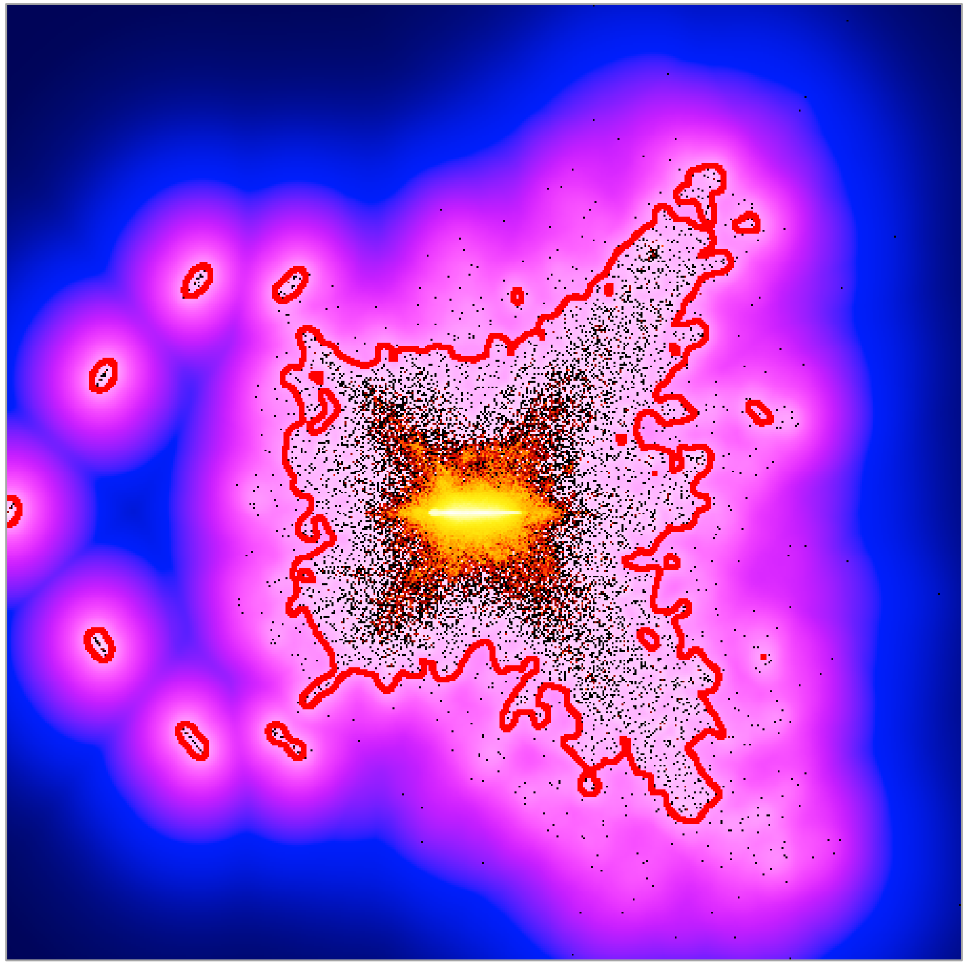


- Sections repeated the least often: discords, or anomalies



Modeling Techniques – Clustering Analysis

- Use unsupervised techniques to label similar observations.
- Observations which aren't assigned to any cluster (or are sufficiently different from the cluster they are matched with) are labeled outliers
- Clustering analysis is modular – different algorithms have different advantages



kNN Applied to Current Data with Anomaly Threshold drawn in red

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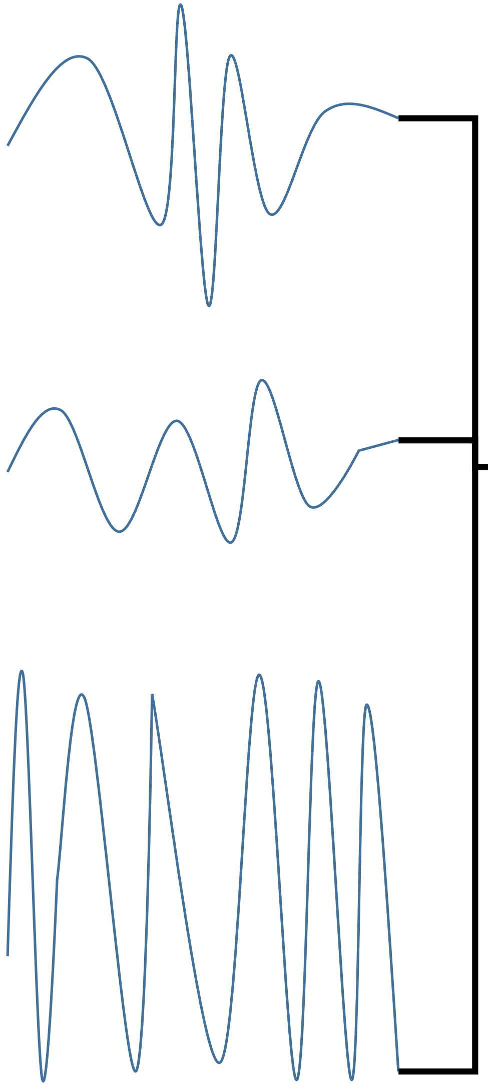
Sample Architecture for Pilot System

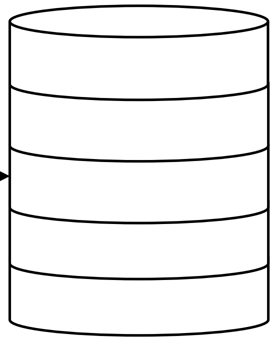


Sensor data collected and initially processed by edge devices. Data stored in databases

Pretrained anomaly detector(s) operate on sensor data in database tables, labels timestamps as "inlier" or "outlier"

Time	Sensor 1	Sensor 2
Timestamp 1	VS1,T1	VS2,T1
Timestamp 2	VS1,T2	VS2,T2
…		
Timestamp 102351	VS1,T…	VS2,T…
Timestamp 102352	VS1,T…	VS2,T…

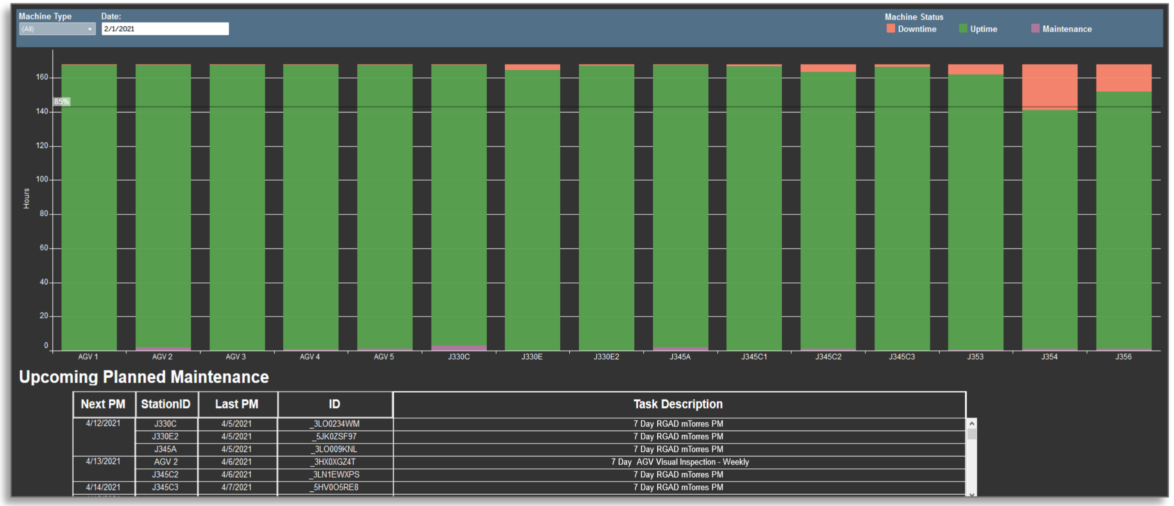
Time	AD 1
Timestamp 1	Inlier
Timestamp 2	Inlier
…	
Timestamp 1	Outlier
Timestamp 2	Outlier

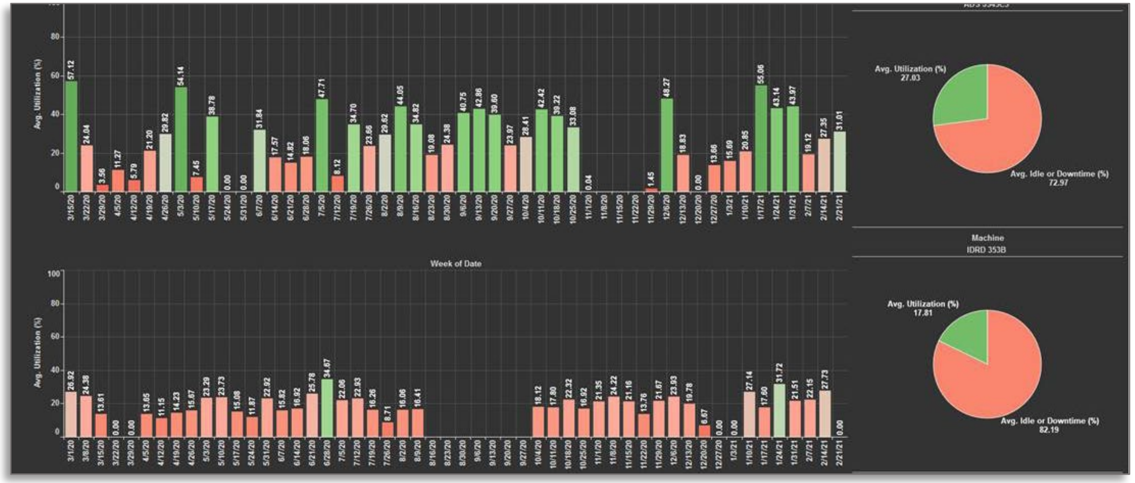


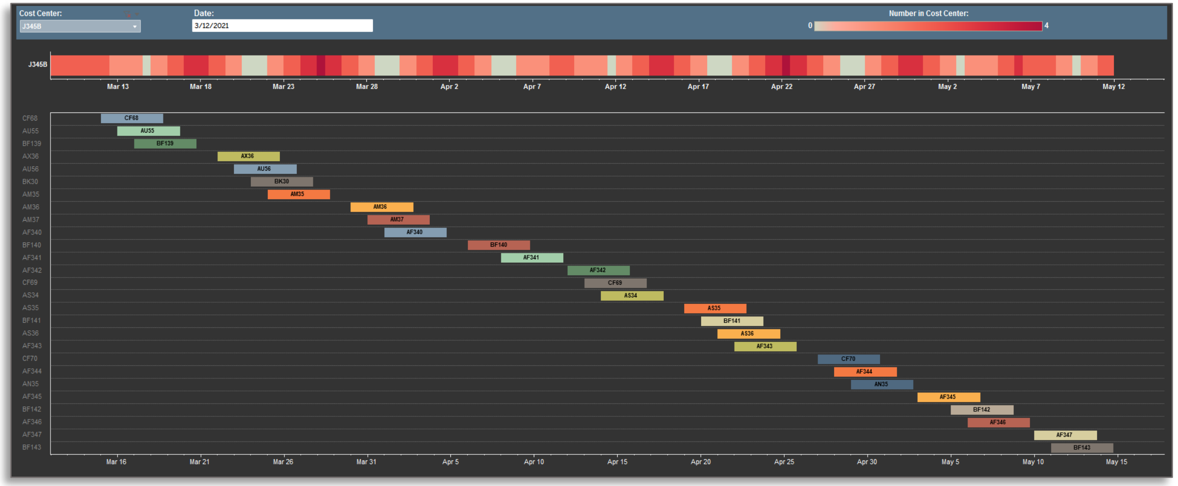
Sufficiently frequent outlying data points trigger notifications/escalations

User Dashboards: Example

Low/no-code environments connect the data consumer to interactive and customizable displays of raw data, processed data, and analytics results







Users Have Access to Several Dashboards for Metrics / Visibility

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

Challenges

- Data collection challenges – wireless vs. wired
  - Wireless, securely encrypted, high-frequency data collection (accelerometers, etc.) rare
  - Wired data collection is expensive and less reliable
- Analytics challenges
  - The right mix of flexibility and specialization
  - Right-sized computing to meet demands at minimal costs

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