Course material on

CONDITION MONITORING OF MARINE MACHINERY USING ARTIFICIAL INTELLIGENCE

A Introduction to Artificial Intelligence and Applications

History of AI

In the 1950's, "Logic Theorist" computer program was used to prove many mathematical theorems. This and a few other programs laid the foundation for modern AI techniques. From here, AI had its ups and downs up until the 90s when there was a boom in AI where various AI were developed to accomplish the daily tasks. For instance, autonomous driving, natural language perception, etc started their development in the 90s. They were termed as intelligent agents which use the physical data from sensors to compute the action to be performed and execute it through actuators.

Objectives of AI:

1. Solve complex problems faster
2. Use lesser computation than conventional techniques for problem solving
3. Complete complex tasks and reduce the amount of time needed to perform specific tasks
4. Facilitate human-computer interaction

Sub Fields of AI:

1. Machine learning
2. Deep learning
3. Natural language processing
4. Cognitive computing
5. Computer vision
6. Fuzzy logic

Use of AI

1. Used to reduce or avoid repetitive tasks.
2. To improve an existing product
3. Used in industries, from marketing to supply chain, finance, food-processing sector.

B Condition Based Monitoring and scheduled monitoring

1. **What are sensors**
   A sensor is a electrical component that senses the physical environment and converts the physical value into an electrical signal to be read by a controlling/monitoring system.
   eg: position, temperature, pressure, humidity, force, vibration sensors etc.
2. **How sensors can be used to check the health of a machine**
   The various sensors placed in and around a machine will keep giving continous data about the measuring parameters. Using this, any abnormality in the system can be quicky spotted from the sensor data that is not within the normal range
3. **Condition monitoring**
   It is the process of monitoring the parameters contributing to the 'health' of a machinery in order to identify any abnormal changes from the standard values which can indicate a potential fault that is about to occur in the future. Condition monitoring plays a vital role in the predictive maintenance of machinery. Some of the common monitoring parameters or techniques as per ISO 17359:2018(en) Condition monitoring and diagnostics of machines — General guidelines are:
   a. Vibration
   b. Temperature
   c. Tribology
   d. flow rates
   e. contamination
   f. power and speed typically associated with performance

Introduction to digital twin

A digital twin is a virtual model designed to accurately reflect a physical object. This is done by fitting and gathering data related to the operation of a real system. This data is then fed into a digital model of the real system to simulate the performance issues and can also be used to optimize the system. With these new inputs, the real world system can now be applied with these new learnings.

generally speaking, digital twin and simulations are not one and the same. This is due to the fact that the digital twin is in a virtual environment whereas the simulation is a offline optimization tool which is used within the digital twin to tweak its performance.

C Forecasting

1. **What is forecasting**
   Forecasting is the process of making predictions based on past and present data. Later these can be compared (resolved) against what happens. For example, a company might estimate their revenue in the next year, then compare it against the actual results.
   Prediction is a similar, but more general term. Forecasting might refer to specific formal

statistical methods employing time series, cross-sectional or longitudinal data, or alternatively to less formal judgmental methods or the process of prediction and resolution itself. Usage can differ between areas of application: for example, in hydrology the terms "forecast" and "forecasting" are sometimes reserved for estimates of values at certain specific future times, while the term "prediction" is used for more general estimates, such as the number of times floods will occur over a long period.

Risk and uncertainty are central to forecasting and prediction; it is generally considered good practice to indicate the degree of uncertainty attaching to forecasts. In any case, the data must be up to date in order for the forecast to be as accurate as possible. In some cases the data used to predict the variable of interest is itself forecast

The various classes of forecasting

a. Qualitative vs. quantitative methods
b. Average approach
c. Drift method
d. Time series methods
e. Relational methods
f. Judgmental methods
g. Artificial intelligence methods
h. Geometric Extrapolation with error prediction
i. Regression method

2. **What is auto regression**
A statistical model is autoregressive if it predicts future values based on past values. Autoregressive models operate under the premise that past values have an effect on current values, which makes the statistical technique popular for analyzing nature, economics, and other processes that vary over time. Multiple regression models forecast a variable using a linear combination of predictors, whereas autoregressive models use a combination of past values of the variable.

3. **What is moving average and how can regression and MA be used for forecasting**
https://otexts.com/fpp2/moving-averages.html
https://otexts.com/fpp2/arima.html

https://www.uky.edu/~dsianita/300/forecast.html

D Bad data Detection

1. **What is bad data**
   Bad data is an inaccurate set of information, including missing data, wrong information, inappropriate data, non-conforming data, duplicate data and poor entries (misspells, typos, variations in spellings, format etc).

   There are many reasons data can be rejected going through a process. From a typo or a missing reference during input validation, to a violation of business logic at some point along the pipeline, all the way through to an issue with pushing data to its target - any of these reasons and more can cause records to be rejected.

   The impact of bad data on your data quality management process can vary depending on how many records get rejected. Missing records can affect downstream processes or analysis, or delay crucial operations such as deliveries or payments. In the worst case, bad data can cause the entire process to fail, leaving mess and inconsistencies behind in the systems involved.
   The more efficiently your error handling system can deal with these rejected records and return them to the processing pipeline, the better your data (and therefore your business insight) becomes.

2. **How to detect bad data**
   Statistical methods using:
   a. Median
   b. Standard Deviation
   c. 3 sigma rule
   d. p-value test

3. **Different methods used to detect bad data**
   Visual methods using:
   a. Bar graphs
   https://matplotlib.org/stable/plot_types/basic/bar.html#sphx-glr-plot-types-basic-bar-py
   b. Line charts
   https://matplotlib.org/stable/plot_types/basic/plot.html#sphx-glr-plot-types-basic-plot-py
   c. Scatter plots
   https://matplotlib.org/stable/plot_types/basic/scatter_plot.html#sphx-glr-plot-types-basic-scatter-plot-py

E Introduction to Python using Spyder-Anaconda package and practical case study

1. **Use of Spyder(Anaconda) package(Open Source), Syntax pertaining to Loops, Conditional statements, functions and file handling.**

   https://docs.spyder-ide.org/current/quickstart.html
   https://docs.spyder-ide.org/current/installation.html
   https://docs.python.org/3/tutorial/introduction.html
   https://docs.python.org/3/tutorial/controlflow.html#if-statements
   https://docs.python.org/3/tutorial/controlflow.html#for-statements
   https://docs.python.org/3/tutorial/controlflow.html#the-range-function
   https://docs.python.org/3/tutorial/controlflow.html#break-and-continue-statements-and-else-clauses-on-loops

2. **How to open and read the contents of a file**

   https://docs.python.org/3/tutorial/datastructures.html
   https://docs.python.org/3/tutorial/datastructures.html#using-lists-as-stacks
   https://docs.python.org/3/tutorial/datastructures.html#using-lists-as-queues

3. **How to Open and write/append data to a file**

   https://docs.python.org/3/tutorial/datastructures.html#tuples-and-sequences
   https://docs.python.org/3/tutorial/inputoutput.html#reading-and-writing-files

4. **Case Study 1**

   Condition-Based Monitoring for Marine Engine Maintenance by Analyzing Drain Cylinder Oil Sample - Famakinwa et al., *Tribology Online* 17.2 (2022): 71-77

   The main goal of the research study was to study effective condition based monitoring of cylinder liners and piston rings by testing cylinder drain oil. The cylinder drain oil is tested by X-ray for the various elements and compositions and they are correlated towards the wear in the cylinder liners and piston ring wears. A machine learning algorithm was used to analyze the test report of the XRF results to correlate elements in the oil samples towards the possible wear amount.

   Condition-based monitoring of cylinder liners includes estimating the remaining useful life of the cylinder liners. Therefore, iron (Fe) quantity in the sampled drain oils was used for physical measurement of the cylinder liners. When sampling for this experiment the condition for the engine is combustion of heavy fuel oil and the turbocharger must be running during sampling. The air charge is from the environment for internal combustion.

This is because water molecules in humid air react with sulfur trioxide to produce unstable sulfurous acid and further reactions produce sulfuric acid in a reversible state. This caused a deposition of corrosive acidic, and it is visible cold corrosion around the bottom dead center of the cylinder liners.

The cylinder lines wall was physically measured using a micrometer diameter gauge. The micrometer diameter gauge is used at fix position relative to the crank angle mark. The interval length was marked on the wall of the liners and the bore size was 600 mm. Ovality was calculated (i.e., amount of wear down) at each marked by subtracting port-starboard distance and fore-aft distance direction positions. This procedure was performed at every 1000 hours of engine service, and the unit is in mm/1000 hours of engine operations for calculations.

The relationship between average wear rates obtained through physical measurements and XRF results for the iron (Fe) concentration in drain oil samples is shown in Fig. 1. The figure indicates the relationship between physically measuring wear down ovality and estimation based on XRF results to access the remaining useful life of the cylinder liners. This is useful when making maintenance policy decisions as on the cylinder liners. The current condition of monitoring cylinder liners is only by physical measurement. Using the XFR coupled with ML method, the wear rate was estimated through only the drain cylinder oil analysis. This method gives the prospect of monitoring the cylinder liners wear without physically measuring marine engine cylinder liners for maintenance decisions.

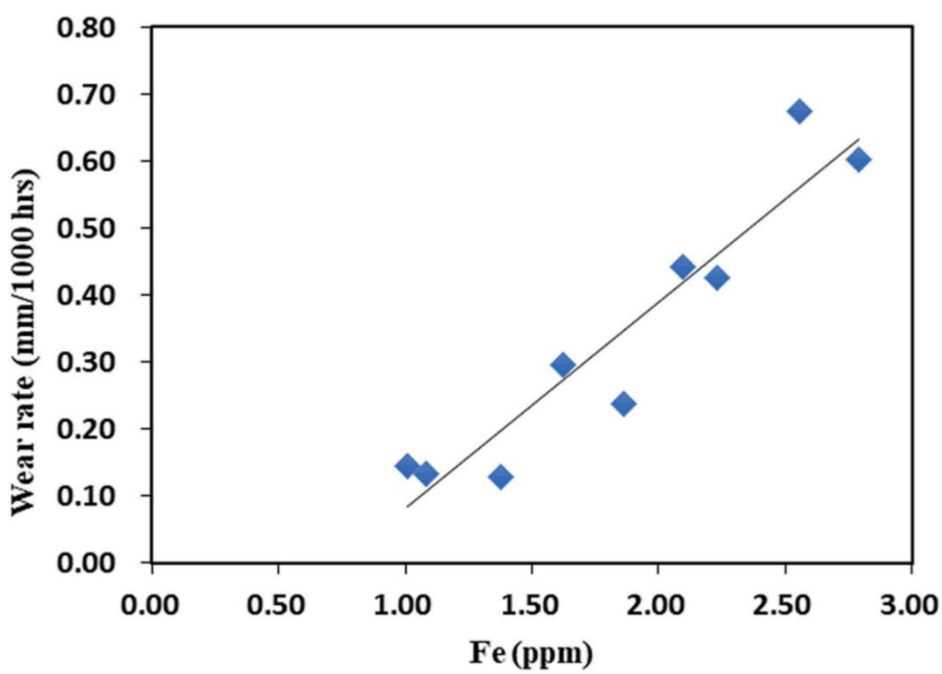

Fig. 1: Graphical representation of average wear rate

5. **Case Study 2**

Sensors Specifications For Maritime Condition Monitoring Based On Failure Mode, Effects and Criticality Analysis (FMECA)- Shan Guan et al., MFPT 2017, *Society for Machinery Failure Prevention Technology*

Sensor selection is an important step during the Condition Monitoring process. The factors affecting the selection of a sensor can be as follows:

1. Determine the variables to be measured
2. Determine the technical specification of sensors for each measurement
3. Determine the availability and affordability of sensors
4. Determine the installation, maintenance plan and calibration procedure of sensors.

From various FMECA and testing results, five types of monitoring technologies are identified, namely Vibration Monitoring, Acoustic Emission Monitoring, Wear Debris and Water in Oil Monitoring, and Thermal Monitoring. In this case study, the sensor specification of vibration monitoring will be given as an example.

Table 1: Important Failure Modes, Failure Criticality and Monitoring Technology of Tunnel Thruster Case Study

Component	**Failure Modes**	**Failure Effects**	**Failure Criticality**	**Sensors**
Electric Motor	Overheating	Short motor life to motor failure	High to Very High	Temperature
Frequency Converter	Temperature induced	Components/ system failure, Won't start	High to Very High	Thermography
Shaft	Shaft failure	Components/ System failure	High to Very High	Vibration, Acoustic Emission, UT
	Sheared Shaft, Shaft failure	Seized	High to Very High	Vibration, Acoustic Emission, UT
Tooth Coupling	Teeth wear away	High vibration to system failure	Medium to Very High	Vibration, Torque, Particulate analysis/ Wear Debris
	Tooth fatigue failure	High vibration to system failure	High	Vibration, Torque
Rolling Bearing	Rolling contact fatigue	Seized to system failure	High to Very High	Vibration, Temperature, Oil analysis (off site)/ Wear Debris
	Plastic deformation	Noisy/Excessive vibration,	Medium to Very High	Vibration

		Seized Motor, Loss of torque		
Bevel Gear	Plastic deformation	Noisy, Vibration, System Failure	Medium to Very High	Oil analysis (off site)/ Wear Debris, Vibration
	Tooth flank contact fatigue	Vibration, System Failure	Medium to Very High	Oil analysis (off site)/ Wear Debris, Vibration
Propeller Blade	Fatigue failure	Loss of Torque, Vibration, System Failure	Medium to Very High	Torque, Vibration, Ultrasonic
Lubrication System	Pressure drop	Components/System failure in long term	Medium to Very High	Oil Pressure
	Overheating	Components/System failure in long term	Medium to Very High	Temperature

Machine vibration can be measured by three representing motion parameters: acceleration, velocity and displacement. The corresponding vibration sensors are accelerometers, velocity vibration sensors, and proximity vibration sensors, respectively. Selection of a suitable vibration sensor depends on the frequencies of interest and signal levels that are involved

To select the correct types of vibration sensors for condition monitoring, the following criteria can be considered:

1. The source of vibration
2. The vibration level and frequency range
3. The temperature range
4. The environment factors (e.g. corrosive condition or combustible atmosphere)
5. The interference with electromagnetic fields (electromagnetic compatibility) or acoustic fields
6. Electrostatic discharge (ESD) conditions
7. Sensor size, cost, packaging and weight considerations.

Table 2: Comparison of Three Types of Sensors for Vibration Monitoring

	Accelerometers	**Velocity Vibration Sensors**	**Displacement Vibration Sensors**
Measuring Parameters	Acceleration	Velocity	Displacement
Sensing Mechanism	Piezoelectric Sensors	Electromagnetic transducer	Capacitance sensors or Eddy-current probe
Major Advantages	Good response at high frequencies; Able to stand	Good response in middle range	Non-contact, No wear; Able to measure both static

	high Temperature; Small size	frequencies; Able to stand high temperature; Low Cost; No external power needed.	and dynamic displacements; Good response at low frequencies
Major Disadvantages	Sensitive to high frequency noise; Higher cost	Low resonant frequency and phase shift; Large footprint; Cross noise	Bounded by high frequencies; Sensitive to Electrical and mechanical noise
Wireless Capability	Commercially available	Not available	Possible, not yet commercially available.
MEMS-based devices available	Commercially available	Not available	Commercially available

Table 3: Technical Specification for Accelerometers Type Vibration Sensors for Tunnel Thruster Condition Monitoring

Tech Specification	**SLD144S Vibration Sensor**	**General Vibration Sensors for Ship Machinery CM**
Nominal sensitivity, main axis	100 mV/g	10-500 mV/g
Transverse sensitivity	Max. 10%	Max. 10%
Typical base strain sensitivity	0.01 m/s2/µ strain	0.01-0.05 m/s2/µ strain
Linear frequency range	2 Hz - 10 kHz (±1dB) (–3 dB at 0.7 Hz)	2 Hz - 10 kHz (±1dB) (–3 dB at 0.7 Hz)
Max. peak acceleration	600 m/s2 = 60 g	100 g
Settling time	3 sec	1-5 sec
Bias point	11 to 13 V (typical 12 V)	11 to 13 V (typical 12 V)
Temperature range	40° C to +125° C (–40° F to 260° F)	0° C to +175° C
Power requirements	24 V /2 - 5 mA	5-24 V (1-10 mA)
Casing	Stainless acid proof steel	Anti-Corrosion/Marine Environment Resist materials preferred
Isolation	Case isolated, > 1 Mohm	Case isolated, > 1 Mohm

Practical study:

Possible data that can be used for the practical study:

a) rotation speed
b) fuel consumption
c) temperature (Cylinder, coolant etc)
d) pressure (lube oil, coolant, turbo charger boost pressure etc)
e) vibration parameters (if any)
f) cylinder exhaust temperature
g) cylinder piston cooling oil outlet temperature
h) cylinder scavenger air fire temperature
i) cylinder liner cooling water outlet temperature
j) scavenging temperature difference of air cooler
k) turbocharger speed