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Condition Monitoring of a Hydraulic System using data-driven Machine Learning methods

Course Name: Systems Engineering

Assignment Part: 01

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1. Condition Monitoring:

Condition monitoring is a process of continuously monitoring one or more operational characteristics of a machine using sensors in order to identify any significant change, which is indicative of a developing fault. This allows predicting the need for maintenance before a deterioration or breakdown occurs. Condition monitoring is a major component of Condition Based Maintenance (CBM) or predictive maintenance, which are based on the actual condition of the machine rather than on some preset schedule [1].

Importance of Condition Monitoring:

- In any light or heavy-duty industry, unexpected faults or shutdown may result in a fatal accident or huge loss of output. Condition monitoring solves these problems by providing useful information for utilizing the machines in an optimal fashion.
- condition monitoring allows to prevent consequential damages to any machinery or system by continuous monitoring of different parameters involved in the smooth functioning of a machine.
- It enables faulty machines to be shut down without destruction or major damage, thus avoiding a long repair time.
- Enables plants to be stopped safely when instant shut down is not feasible.
- Detects reductions in machine efficiency or increased energy consumption.
- Reduces maintenance cost and increases equipment reliability.
- Maintains product quality and prevents degradation of standards caused due to defective machinery.

Based on methods applied, condition monitoring can be classified into two types:

a. Trend Monitoring: It is the continuous collection, measurement and interpretation of data during machine operation, to indicate a trend or variations in the condition of the machine or its components. This involves the selection of certain indication of machine or component deterioration and the study of the trend in this measurement with running time to indicate if or, when the deterioration is exceeding a critical rate. Trend monitoring can give a lead-time before the deterioration reaches a critical level at which, the machine would have to be shut down. This lead-time is one of the main advantages of using trend monitoring rather than reactive monitoring techniques.

b. Condition checking: It is where measurements are taken with the machine running and the instantaneous condition derived from the collected data are compared to an ideal or expected condition of the machine. To be effective the measurement must be accurate and quantifiable, and there must be known limiting values which must not be exceeded for more than a certain number of permitted further running hours. This method can be less flexible than trend monitoring, as the latter is more useful in terms of providing lead-time as well as machine knowledge. However, it can be particularly useful, however, in a situation where there are several similar machines operating together where, comparative checking can be done between the machine which is monitored, and other machines which are known to be in new or good condition.

Based on the type of parameter, condition monitoring can be classified into follows:

a. Thermography
b. Vibration Monitoring
c. Shock pulse Monitoring
d. Temperature Monitoring
e. Wear Debris Analysis
f. Motor Current Monitoring
g. Noise monitoring

Condition monitoring applies to a diverse set of industries. Some of them are,

a. Thermal power industry
b. Mining Industry
c. Manufacturing Industries
d. Automobile industries
e. Power Stations
f. Transportation Sectors
g. Astronomy
h. Medical Industry etc.

2. Fault Classification:

Once any deviation from the nominal characteristics of the variables is detected, the next step is to identify the magnitude of the abnormal behavior. This is done by combining qualitative as well as quantitative information, in order to draw inferences regarding the state of the machine. The system takes all the possible faults projected by the available data, and compresses them into successively finer categories. Each category or state has an associated degree of likelihood, which is determined from the training data set [2].

Strategy:

After collection of a large stream of data from the sensors, classification models are trained on the training set of a labeled dataset to precisely identify the faults and abnormalities. Among them, the most widely used models are *K*-nearest-neighbors algorithm (*k*NN), Support Vector Machines (SVM), Artificial Neural Networks (ANN) etc.

The basic steps in fault classification include reduction of dimensionality of a large data set in order to overcome the “curse of dimensionality”. Feature extraction algorithms help in reducing dimensionality by separating the redundant features from the important and informative ones [3]. This allows for feature selection the relevant features are selected for construction of the model. After successful training of the models, the remaining data set are tested in the algorithm and output results are classified based on their state of fault and severity.

Among the mentioned techniques, *k*NN method does not possess automatic feature extraction capabilities and the processing time on large datasets with this model is also relatively high. For this, certain data pre-processing techniques like Principal component analysis(PCA), Adaptive linear approximation (ALA) Linear discriminant Analysis (LDA), or Best Fourier Coefficients (BFC) etc. are used along with this model to reduce dimensionality [3]. For industrial purposes, complex classification techniques such as SVM or ANN can provide more robust performance.

The SVM model can provide nonlinear mapping using kernel methods and performs generalization efficiently, even with small training data [4]. However, general SVMs do not have automatic feature extraction and are often used with a data pre-processing technique. Moreover, the low speed of SVM technique in the training phase is also a limitation.

ANN techniques are more efficient for these purposes as they possess efficient self-learning capabilities of complex relations and can perform automatic feature extraction by its method of weight allocation to node connections. This relieves the model from adding any data pre-processing technique. However, ANN models often require supervised learning to prevent the model from overfitting the training set [5].

3. Machine Learning Algorithms used for Classification:

Deep Neural Networks (DNN)

Neural networks (NN) can be described as a data processing system consisting of a large number of simple, highly interconnected processing elements (artificial neurons) in an architecture, inspired by the structure of the cerebral cortex of the brain [7].

Architecture:

The architecture of neural networks is based on the number of layers and the number of nodes in each layer. The general architecture of a neural network is shown in Fig. 1. These structures are usually called a perceptron. Each perceptron has m number of inputs with individual connection weights. A perceptron models a neuron by taking a weighted sum of inputs and sending an output. If the sum is greater than the adjusted threshold value, then the output sent is 1, otherwise it is 0. This threshold value is also called an activation function.

The inputs and connection weights can be either positive or negative real values, both. If the feature of some input causes the perceptron to fire, its corresponding weight will be positive; if the feature inhibits the perceptron, the weight will be negative.

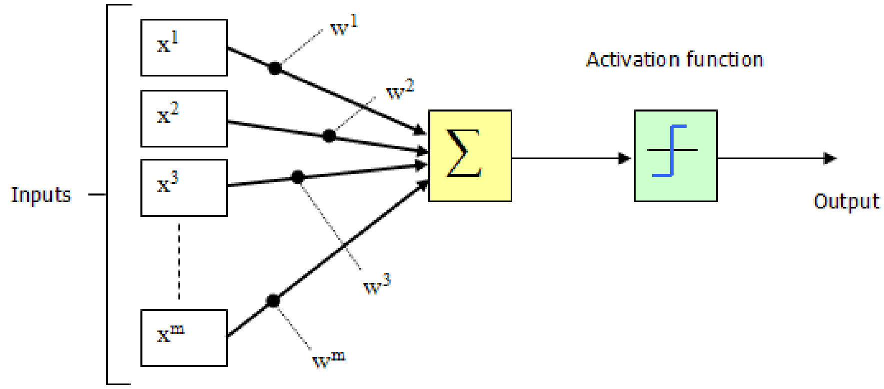

Fig. 1: General Architecture of Neural Network (Perceptron). [7]

Single perceptron neurons neural network can be used to model linearly separable functions (e.g., the OR function). However, for non-linear functions and other more complex functionality, it requires an extra layer. This layer is called the Hidden Layer. Each perceptron can also consist of an adjustable threshold processor also known as the Bias. The bias can be treated as an input node in each layer and it retains a value of +1. This bias feeds a constant value through the activation function called the Intercept term. This term can shift the activation function to the left or to the right.

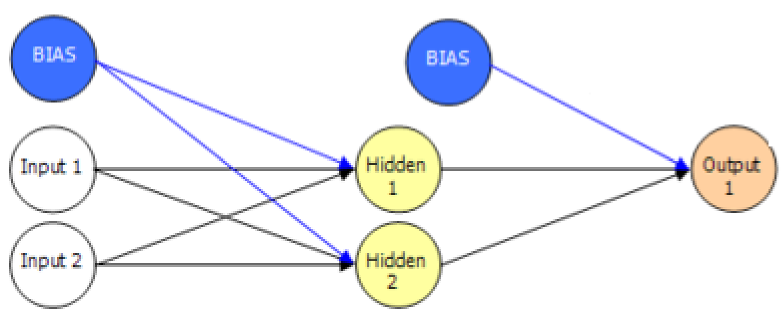

Fig. 2: A Multi-layer Neural Network. [7]

Activation Function:

Activation functions limit the output of a neuron to a certain value. These functions can be any one of Linear, step, ramp, sigmoid, hyperbolic tangent, and Gaussian functions. Most commonly used are Step Function and Sigmoid Function.

(i) Step Function: It is a basic on/off function stated as,

$$f(x) = \begin{cases} 0, & \text{if } x<0 \\ 1, & \text{if } x\geq 0. \end{cases}$$

Step functions are mainly used for linear tasks. If an activation function is linear, then no matter how many hidden layers, the final output will always be a linear combination between input and output. Hence, non-linear or complex problems cannot be solved with this function. In this case, a derivative function is the best option.

(ii) Sigmoid Function: To accomplish non-linear complex functions, backpropagation neural network technique is applied. In this technique, the Sigmoid function allows differentiation to minimize the Cost Function (the function that compares the obtained output of a layer to the expected output). This allows the neural network to optimize the values of the connection weights and the bias using Gradient Descent so that the Cost Function ultimately reduces.

Taking the weighted sum of all inputs of a layer and the bias, we find the value z of a Sigmoid neuron [7].

$$z = \sum_{i=1}^{m} w_i x_i + bias$$

$$\text{Sigmoid Function, } \sigma(z) = \frac{1}{1+e^{-z}}$$

Training of the Network: The perceptron is trained to respond to each input vector with a corresponding target output ranging from 0 to 1. The learning rule converges on a solution in finite time provided that, a solution exists. This is performed mainly in two steps

(i) Bias Correction:

$$b = b + (T - A)$$

(ii) Weight values Correction:

For all inputs i:

$$W(i) = W(i) + [T - A] * P(i)$$

Where **W** is the weight vector, **P** is the input vector, **T** is the expected result that the neuron should have shown, **A** is the actual output of the neuron, and **b** is the bias. [7]

Learning Mechanism in Neural Network:

The learning mechanisms are important for optimizing the weights of the connections. These are classified as follows:

(i) Supervised Learning: A neural net is said to learn supervised, if the desired output is already known. While learning, one portion of the input data is given to the network's input layer. This data is transmitted through the network to its output layer. The output layer generates an output pattern, which is compared to the expected result. Depending on the difference between output and target, an error value is computed. This output error indicates the network's learning pattern, which can be controlled by an "imaginary" teacher. The greater the computed error value is, the more the weight values will be needed to change. Once the error value reaches a minimal point, the network is considered as trained

(ii) Unsupervised Learning: Neural networks with unsupervised learning method do not have target outputs. During the learning process, the weights of such network are "arranged" ina certain range, based on input values, With the aim to grouping similar units close together in certain areas of the range [8].

Support Vector Machine (SVM)

A Support Vector Machine (SVM) is a common supervised learning model that is used to analyze classification, regression and outlier detections. In this method we plot every data in n-dimensional space, then decision planes are calculated which separates the data according to their class. A decision plane – commonly known as hyperplane is a plane, which separates the sets of objects having different class representatives.

For example, in figure 3 we have two sets of data. Suppose the blue circles are of class A and the red squares are of Class B. Now we want to separate the classes by drawing a line between them. Many possible hyperplanes can be chosen to separate the two classes of data points. The main motive of SVM is to find a hyper-plane that has the maximum distance between data points of both classes. Data set closest to the optimal hyperplane from both side are called Support Vectors. If support vectors are removed from the data set, the position of hyperplane may be changed that is why these are the critical elements for every data set [9].

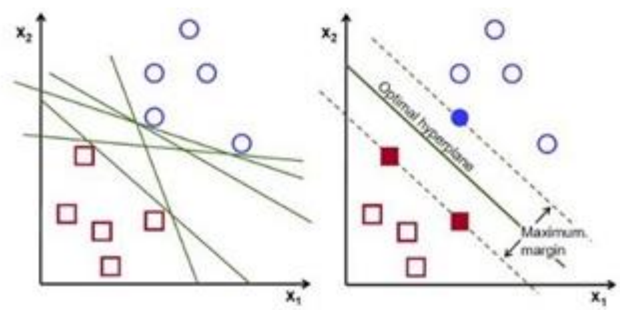

Fig. 3: Hyperplanes in SVM model [9].

Defining the Hyper-plane mathematically:

If ($\mathbf{x}_1$, y1), ($\mathbf{x}_2$, y_2)...... ($\mathbf{x}_n$, y_n) are data sets of n points and y_i is either 1 or -1 indicating the class for which $\mathbf{x}_i$ belongs. If b is bias from any point then hyperplane H would be such

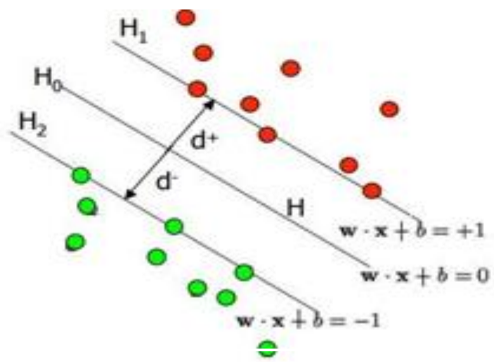

Fig. 4: Data Set distribution by Hyperplanes [10]

that w.$\mathbf{x_i}$+b ≥+1 when y_i=+1 and w.xi+b ≥-1 when y_i=-1. From figure 4 we see H_1 is the plane of w.$\mathbf{x_i}$+b ≥+1 and H_2 is the plane for which, w.$\mathbf{x_i}$+b ≥-1. H_0 is the median plane for which w.$\mathbf{x_i}$+b=0. In figure 3 d+ and d- represents the shortest distance to the closest positive and negative points respectively. The distance from H_0 to H_1 is |w.$\mathbf{x}$+b|/||w||=1/||w||, and the total distance is from H_1 to H_2 is 2/||w||. In order to maximize the margin we need to minimize ||w||. Since there are no data points between H_1 and H_2, we can combine these two conditions writing $\mathbf{y_i}$ ($\mathbf{x}_i$.$\mathbf{w}$) ≥1, where, w is a weight vector [10].

Tuning Parameter Kernel

When there is too many data for which linear separation between classes becomes impossible, the Kernel trick is used. In Kernel trick low dimensional input space data are transformed using some useful mathematical functions. The transformation is done in such a way that it converts non-separable problem into separable problem. These functions are known as Kernel's function. Kernel's function is mostly useful in non-linear separation problem. To find linear Kernel, the equation for predicting a new input using the dot product between the input(x) and support vector(x_i) may be calculated by the following equation:

$$F(x)=B(o)+sum(a_i*(x,x_i)). \quad [11]$$

This equation calculates the inner products of a new input vector(x) with other support vectors in training data. Value of B(o) and a_i are estimated from the training data using learning algorithm.

The polynomial kernel can be written as,

$$K(x,xi) = 1 + sum(x * xi)^d. \quad [11]$$

and exponential as,

$$K(x,xi) = exp(-gamma * sum((x—xi^2)). \quad [11]$$

Two other commonly used Kernel Tricks are Polynomial Kernel SVM and Radial Kernel SVM

<u>Polynomial Kernel SVM:</u>

The polynomial Kernel is used for curved lines in the input space. The following equation is used in this case,

$$K(x,x_i)=1+sum(x*x_i)^d$$

In this case the degree of the polynomial must specify by learning algorithm.
Note : for d=1 the equation becomes same as the linear Kernel equation

Radial Kernel SVM:
The Radial basis function kernel, also called the RBF kernel, or Gaussian kernel, is a kernel that is in the form of a radial basis function (more specifically, a Gaussian function). The RBF kernel is defined as,

$$K(x,xi) = exp(-\gamma * sum((x - xi^2)),$$

where γ is a parameter that sets the "spread" of the kernel. In this case, the value of γ is specified to the learning algorithm. The value of γ often lies along $0< \gamma<1$ [11].

4. Hydraulic System:

Hydraulic system is a system that consists of different equipment like motor, pump, accumulator to perform a work by the flow of pressurized fluid. It is one of the most efficient ways to do heavy like lifting, moving any repetitive work. Hydraulic systems work based on the principal of Pascal's Law. Pascal's Law state that the pressure in an enclosed fluid is uniform in all the directions.

Hydraulic System Components:

All hydraulic systems consist of six basic components. These are Reservoir, Pump, Electric Motor, Valves, Actuator and piping.

a. Reservoir: It holds the fluid and transfers it into the hydraulic system. It also helps to remove air and moisture from the stored fluid.
b. Pump: The pump moves fluid through pressure. The hydraulic pumps are specified by its power consumption, driving speed, flow rate, pressure delivered and the efficiency of the pump. The hydraulic pumps are generally two types. These are centrifugal pump and reciprocating pump.
c. Electric Motor: It drives the pump. Both AC and DC motors are used to power hydraulic pumps. The most commonly used electric motor is three phase AC motors.
d. Valves: Valves are used to control pressure, flow rate and flow direction. It controls the operation of the actuators and regulate pressure. Valve also works to control fluid that how much it has to go on any portion of the circuit. Valves are mostly three types. These are pressure control, volume control and directional control valves. However, some valves have multiple functions. It is important to select proper rating of valve before installing it to the system.

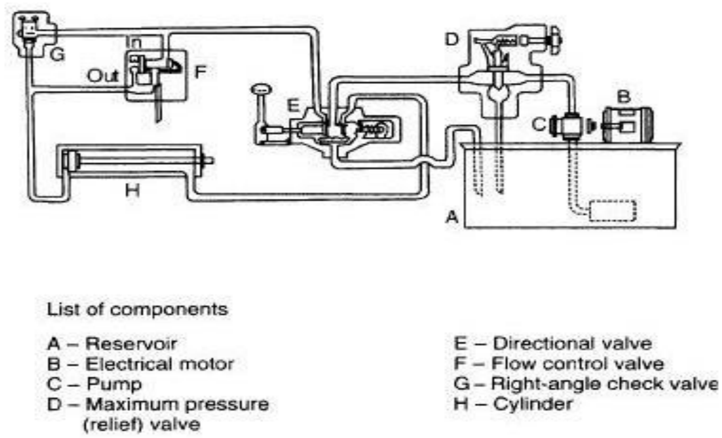

Fig. 5: Schematic of a basic Hydraulic System [12].

e. Actuator: Actuators may be either cylinders or motors, which convert the energy of liquid to mechanical force or torque. Actuator can be linear or rotary. Linear actuator provides force and motion outputs along a straight line. It is commonly called as cylinder. On the other hand, rotary actuator produces torque and rotating motion.
f. Piping: It is used to pass the fluid from one portion to another portion. Piping can be done in different ways. In hydraulic system the most common types of pipe lines are pipes, tubing and flexible hoses.

Figure 5 shows the necessary features of a basic hydraulic system; here linear hydraulic actuator is used.

In most cases, high density incompressible oil is used as fluid. First, it is filtered and pumped by the hydraulic pump. The rating of pump is determined before designing the system. These pumps usually deliver constant volume on each revolution of the pump shaft. A pressure regulator is then used to prevent accident in pump due to high pressure. Valves control the amount of pressure that the pump delivers. The motor powers the pump. It takes hydraulic fluid from the storage tank and delivers it to the rest of the hydraulic circuit. Normally the speed of the pump is fixed and it delivers constant volume in each revolution.

Open Loop and Closed loop System:
Open Loop System: In open loop system, pump inlet and motor outlet are connected through tank. Open center circuit pump is used for continuous flow of liquid. The liquid is sent back to the tank by a control valve’s open center. If the control valve is centered it makes an open return path to the tank besides the liquid is not pumped in a high

pressure. A pressure relief valve is used to send the liquid into tank if the pressure gets too high [13].

Close loop Connected System: In close loop connected system, pump inlet is connected directly. Here a gear pump is used so that it supplies filtered air to the low pressure side of the circuit [13].

Variables effecting the operation of the plant:

1. Temperature:

In hydraulic system, stability of fluid temperature is important for the success of mechanical system. Fluids have limit to work efficiently under a certain temperature range. If the system's fluid exceeds this limit, the machine will loss stability and may experience conditional failure. If this failure is kept unchecked, it may result performance degradation of the system.

Temperature has both effect on component materials and machine efficiency. If the temperature of the system becomes very low, the viscosity of fluid will increase and finally will reach a critical level where the fluid may stop flowing or flow in a low rate. This low flow rate will affect the pump performance as well as motor efficiency. On the other hand, high temperature may cause disruption of working fluid, degrade system performance and apparently reduce the lifespan of different working components. The normal operating temperature range for hydraulic system is from 110 to 130°F. For optimum performance, oil temperature should keep around on 120° F and never allow to exceed 150°F [14].

2. Pressure:

In hydraulic system, there may be pressure drop or rise depending on different situations.

Effect of overpressure: There are pressure control devices in every hydraulic system, however, if somehow any of these devices fail to operate, the system may experiences a pressure more than its designed one. Overpressure may cause loss of lubrication, valve plate separation and mechanical damage. Increase of operating pressure increases the load on lubricated surface. If system pressure exceeds its design limit, loads can cause boundary lubrication. Besides, overpressure may separate the cylinder barrel from the valve plate. Moreover, overpressure can damage various mechanical parts of the system like motors, pumps, valves and cylinders [15].

Effect of pressure drop: In hydraulic system, pressure drop means generation of heat. That means any internal leakage on the system may cause overheating to the circuit and finally this overheating may damage various components of the system [15].

3. Vibration and Noise:

Pumps are the main source of noise and vibration. Cylinders and motors can also introduce noise in the system. Pump generates flow ripples that interact with other components in the system. These ripples create harmonic waves resulting noise in the system. Excessive noise leads to damage piping system and other components. Therefore, if vibration is found, firstly we need to check the pump, we can check the alignment of the drive shafts. Faulty pipework, presence of air, loose mounting can be also responsible for noise and vibration. If proper steps are not taken in time, the efficiency of the system may drop drastically.

6. Machine Learning Framework of Algorithms for Fault Classification:

From the data set provided for a Complex Hydraulic System Test Rig, the following machine learning framework shall be followed for fault classification of the respective variables of Cooler Condition, Valve Condition, Internal Pump Leakage, Hydraulic Accumulator and Stable Flag.

Process Flow	Description
Multivariate, Time Series Data	• The provided time series data set will be selected for feature extraction based on functions that represent the signal shape (slope of linear fit, position of maximum value) and distribution density characteristics (median, variance, skewness and kurtosis).
↓	
Feature Extraction	• Feature Extraction will be performed using the Linear Discriminant Analysis (LDA) technique.
↓	
Feature Selection	• The data set providing the non-redundant features will be selected for further optimization of the model.
↓	
Training of Machine Learning Model with 70-80% of Data Set	• The machine learning models will be trained by means of Supervised Learning technique to increase the efficiency of the models. In case of Deep Neural Network, the Backpropagation technique can be used.
↓	
Testing of remaining Data set	• The remaining data set will be tested in the trained models for classification of fault conditions of the parameters involved.
↓	
Classification of Faults and Condition Analysis	• The results obtained from the different models representing fault conditions of the equipments will be analyzed.

Fig. 6: Machine Learning Framework for Fault Classification.

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