Sensors and Tribological Systems: Applications for Industry 4.0

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ABSTRACT

Purpose: The involvement of wear, friction and lubrication in engineering systems and industrial applications makes it imperative to study the various aspects of tribology in relation with advanced technologies and concepts. The concept of Industry 4.0 and its implementation further faces a lot of barriers particularly in the developing economies. Real-time and reliable data is an important enabler for implementation of the concept of Industry 4.0. For availability of reliable and real-time data about various tribological systems is crucial in applying the various concepts of Industry 4.0. This paper attempts to highlight the role of sensors related to friction, wear and lubrication in implementing Industry 4.0 in various tribology related industries and equipment.

Design/methodology/approach: A through literature review has been done to study the interrelationships between the availability of tribology related data and implementation of Industry 4.0 are also discussed. Relevant and recent research papers from prominent databases have been included. A detailed overview about the various types of sensors employed in generating tribological data is also presented. Some studies related to application of machine learning and Artificial Intelligence are also included in the paper. A discussion on fault diagnosis and cyber physical systems in connection with tribology has also been included.

Findings: Industry 4.0 and tribology are interconnected through various means and the various pillars of industry 4.0 such as big data, Artificial Intelligence can effectively be implemented in various tribological systems. Data is an important parameter in effective application of concepts of industry 4.0 in the tribological environment. Sensors have a vital role to play in the implementation of industry 4.0 in tribological systems. Determining the machine health, carrying out maintenance in off-shore and remote mechanical systems is possible by applying online-real-time data acquisition.

Originality: The paper tries to relate the pillars of Industry 4.0 with various aspects of tribology. The paper is a first of its kind wherein the interdisciplinary field of tribology has been linked with industry 4.0. The paper also highlights the role of sensors in generating tribological data related to the critical parameters such as wear rate, coefficient of friction, surface roughness which is critical in implementing the various pillars of industry 4.0.

Keywords: Industry 4.0; Sensors; Tribology; Machine Learning; Artificial Intelligence

1. Introduction

The extensive involvement of friction, wear and lubrication in the variety of engineering applications makes tribology an important field for the overall developments in the industrial and economic fronts(Haq and Anand, 2018b) (Kerni, Raina and Haq, 2018)(Kerni, Raina and Haq, 2019). According to Stachowiak (Stachowiak, 2017), "*during the industrial revolution, it became clear that without advancements in tribology the technological progress would be limited*." Derived from the Greek word "*tribos*" the word "Tribology", deals with the science of friction, wear and lubrication. Tribology being a surface phenomenon, surface roughness plays a vital role in determining the tribological properties of materials. This term was officially coined by Jost in 1966 stating it as the science of interacting surfaces and the relative motion among them(Jost, 1966). Moreover, it is an interdisciplinary field involving the concepts of chemistry, physics, material science, mathematics and engineering(Charoo and Wani, 2017)(Anand *et al.*, 2017). Despite its contribution in almost all processes in industry and our day-to-day life, it continues to be the unknown for most of field. As reported by Popov in 2018, the field of tribology remains unknown for most of the engineering researchers (Popov, 2018). Tribology is the backbone of every industry involving machinery. With each industrial revolution, the machinery became more sophisticated and more emphasis on their maintenance gave the space for tribological research. Enrico described the various stages of tribological era's in accordance with the industrial revolution(Ciulli, 2019).

The industrial and tribological revolution can be divided into the four different eras: from 1750 to 1850, from 1850 to 1950, from 1950 to 2000, and from 2000. The first industrial revolution started in year 1784, which very close with the first tribological studies performed by coulomb in year 1781. Second industrial revolution started in 1870 that is said to be the motivation for developments in the field of lubrication by Reynold. As Jost Reports officially coined the term "tribology" in year 1966, the third industrial revolution came into existence (1969). With further advancements in the field, new term called tribotronics (2008) was coined which gave the way for fourth industrial revolution (2011). The Fundamental industrial and tribological developments and there relation with each other is shown in Figure 1(Ciulli, 2019).

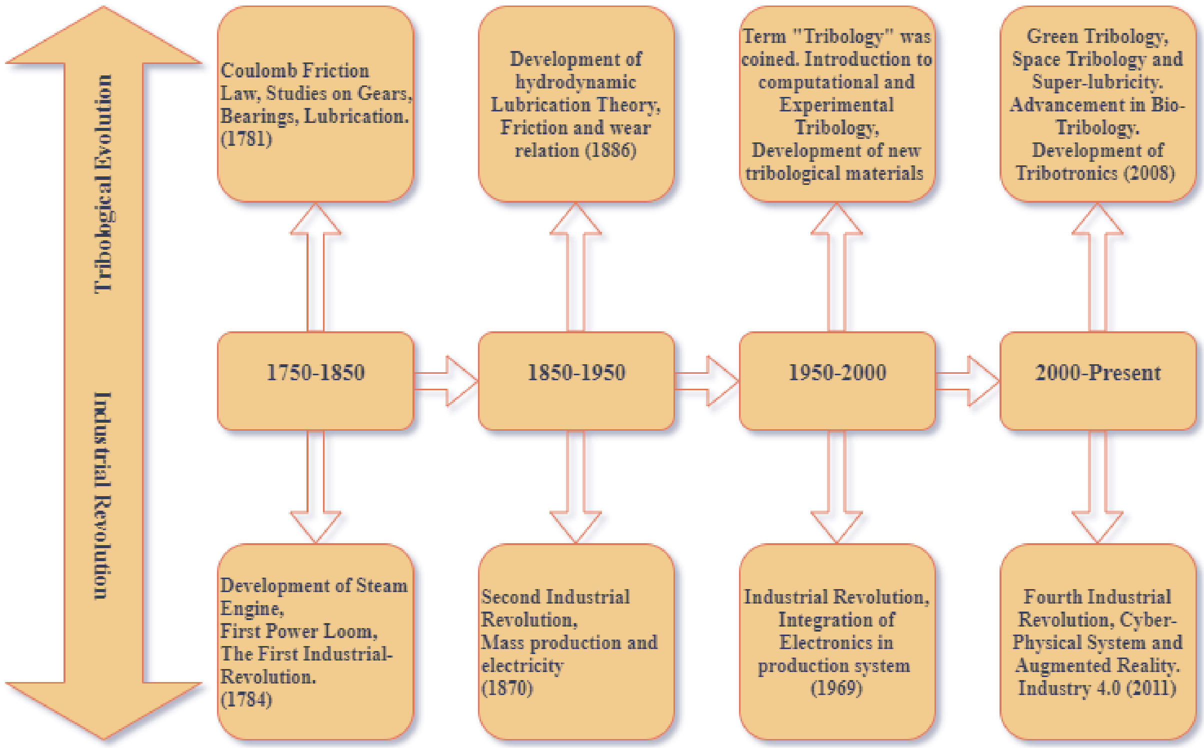

Figure 1: Tribological phases in industrial development

From the above information, it is quite evident that there is the deep relation of tribology with the industrial development and with advancement in the industries, there must be significant change in the modalities of tribology. Tribology plays an important role in the energy and environmental issues. Kenneth has reported the impact of tribology on the CO_2 emission and energy consumption(Holmberg and Erdemir, 2019). Around 23% of the total global energy goes to overcome the energy losses from tribological contacts. From the economic point of view, around 2,536,000 million euros annually are losses generated due to the tribological contacts, in which 73% is due the friction and 27% is due to the wear. By applying the new methodologies of tribology and materials engineering, it is estimated that 40% of total energy loses due to friction and wear can be reduced by a long-term plan of 15 years and 18% in the short-term plan of 8 years (Holmberg and Erdemir, 2017).

Tribological studies are very important for the industrial setups as they are main energy consumption sectors. It is estimated that 15%-20% of the total energy in paper mill industry is used overcome the friction (Holmberg *et al.*, 2013). In mining industry, around 40% of the total energy consumption goes to overcome the friction (Holmberg *et al.*, 2017). There is the general estimation that in the industrial sector, around 20% of energy consumption goes to overcome the friction and 14% of the friction loses goes in the account of wear loss (Holmberg and Erdemir, 2017).The total percentage energy loss due to friction in each sector is shown in the Figure 2, wherein it can be seen that the energy losses due to transportation, energy and industrial sectors are huge and can led to huge economic impact on nations and corporations(Nosonovsky and

Bhushan, 2010)(Ul Haq *et al.*, 2021). Therefore, there is a dire need to look for better tribological practices which would reduce these losses due to friction.

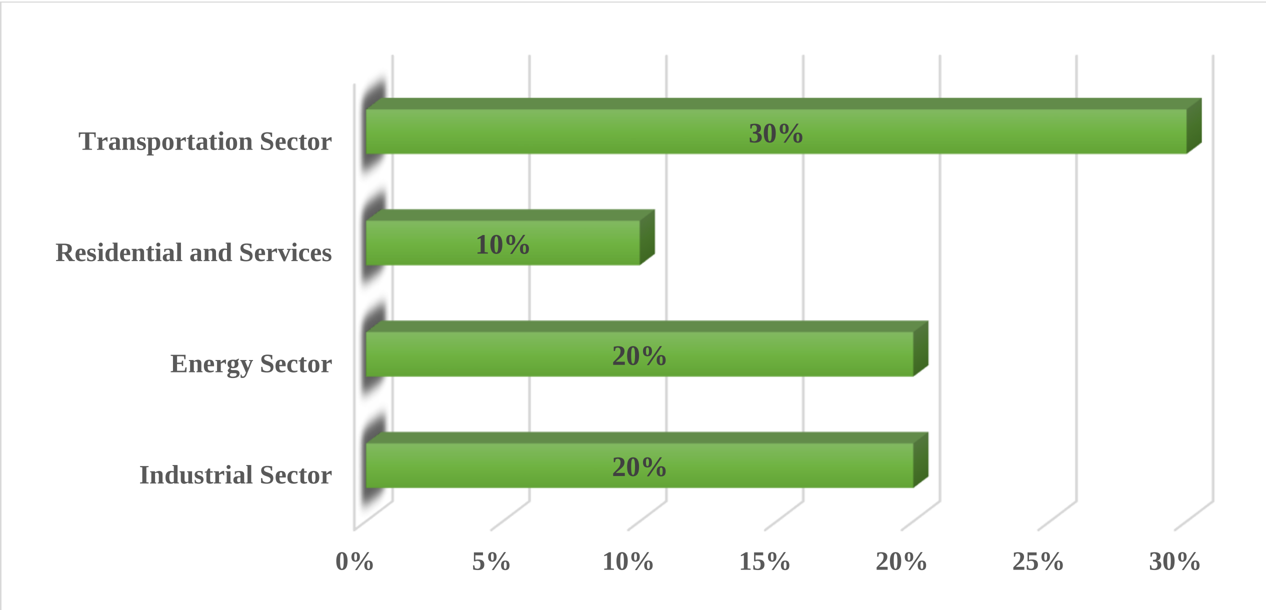

Figure 2: Percentage of Total Energy loss due to friction in various sectors(Holmberg and Erdemir, 2017)

Further, Figure 2 also indicates that tribology is very important from economic, energy, and environment point of view. This can only be done by employing high-end sensors in the tribological apparatus, moving towards the tribology 4.0 and cyber physical systems. The digitalization of tribology is very important for the current trends in industry 4.0. The ultimate aim of the tribology society is to make the tribology autonomous to provide results that are accurate. From the above literature we mentioned how the industrial revolution was accompanied by the tribological developments or the digitization of the tribology. To meet the needs of industry 4.0, the tribology got integrated with computer systems to provide the better coatings for surfaces, material for tools, Lubrication for better performance.

Tribological data from the sensors is analyzed by the AI and ML algorithms to provide the better understanding of the process and reducing the time and cost by modelling the process and predicting the impact of various experimentation conditions on various tribological properties. Figure 3 shows the main components of tribological system interacting with the sensors and actuators for producing the real time data, which can easily be interpreted with the help of software developed for the said cause. The sensors installed on the system provide the information for vibration, temperature, friction, wear, oil condition etc. The signals are sent to the control unit, which are processed to give the output based on the computational algorithms fed to the decision or real-time data acquisition part.

The current paper is structured in manner to focus on various aspects of tribological data w.r.t the concept of Industry 4.0. Apart from discussing the basic concepts, relevant and recent literature and research studies have been discussed with an aim to relate tribology with Industry 4.0. Prominent research databases have been searched using relevant keywords. Based on the literature studied, it came to the fore that there is a need to relate the various aspects of tribology with the concept of Industry 4.0. The paper is state of art review, which encompasses almost all the important developments in the field of sensors and the tribology.

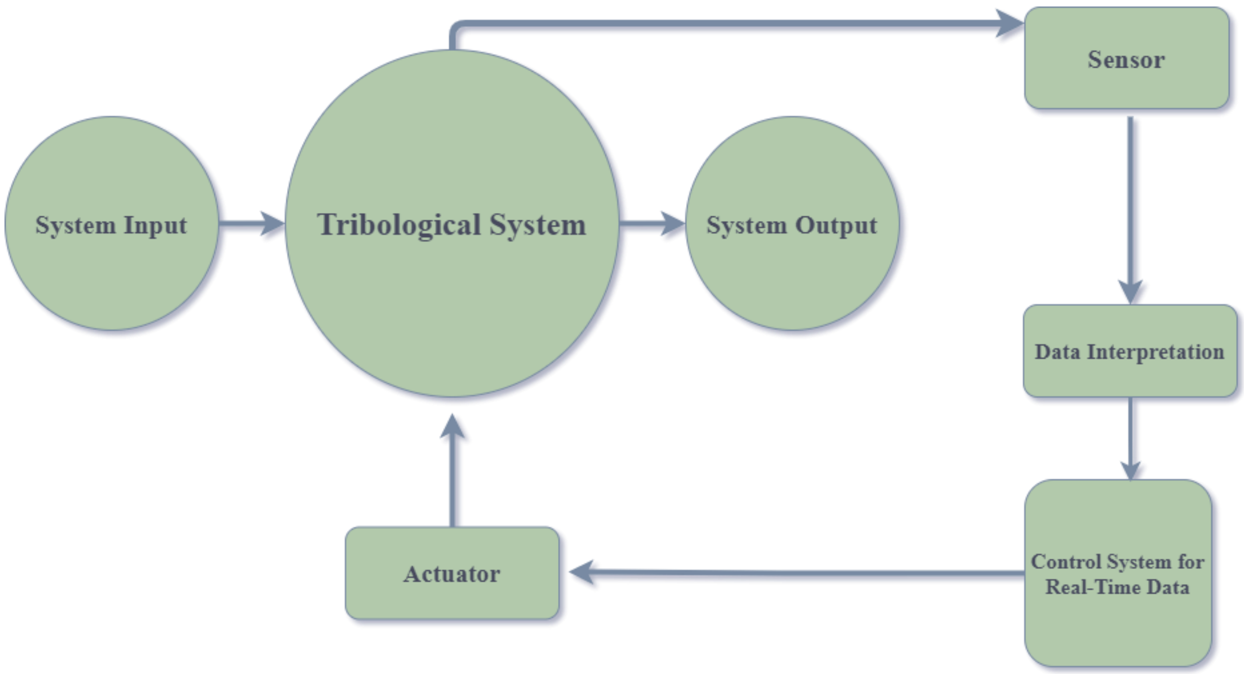

Figure 3: Tribological system with sensors

2. Sensors and Tribology

The study of tribology with electronics is very important. With the advancements in the electronics, sensors that are more efficient are developed. Main purpose of these sensors is to detect the lubrication condition, wear, friction, temperature and vibration(Murphy *et al.*, 2005). The deep interrelation between the tribology and electronics was reported in 2008 and term tribotronics was coined (Glavatskih and Höglund, 2008). The term tribotronics is equipped with the online sensors, which help us get the real-time data; hence, the machine performance and health can be analyzed and comprehended in much better way. With the better understanding of sensors for tribology, the rundown time for long-range applications of machine can be reduced. This is mainly done by the study of vibration patterns and thermography (Khan and Starr, 2006)(Younus and Yang, 2012). Some important applications of sensors in tribology are lubricant health monitoring, wear studies and surface roughness studies. Figure 4 shows the importance of sensors in the field of tribology specifically for wear, friction, lubrication and surface roughness.

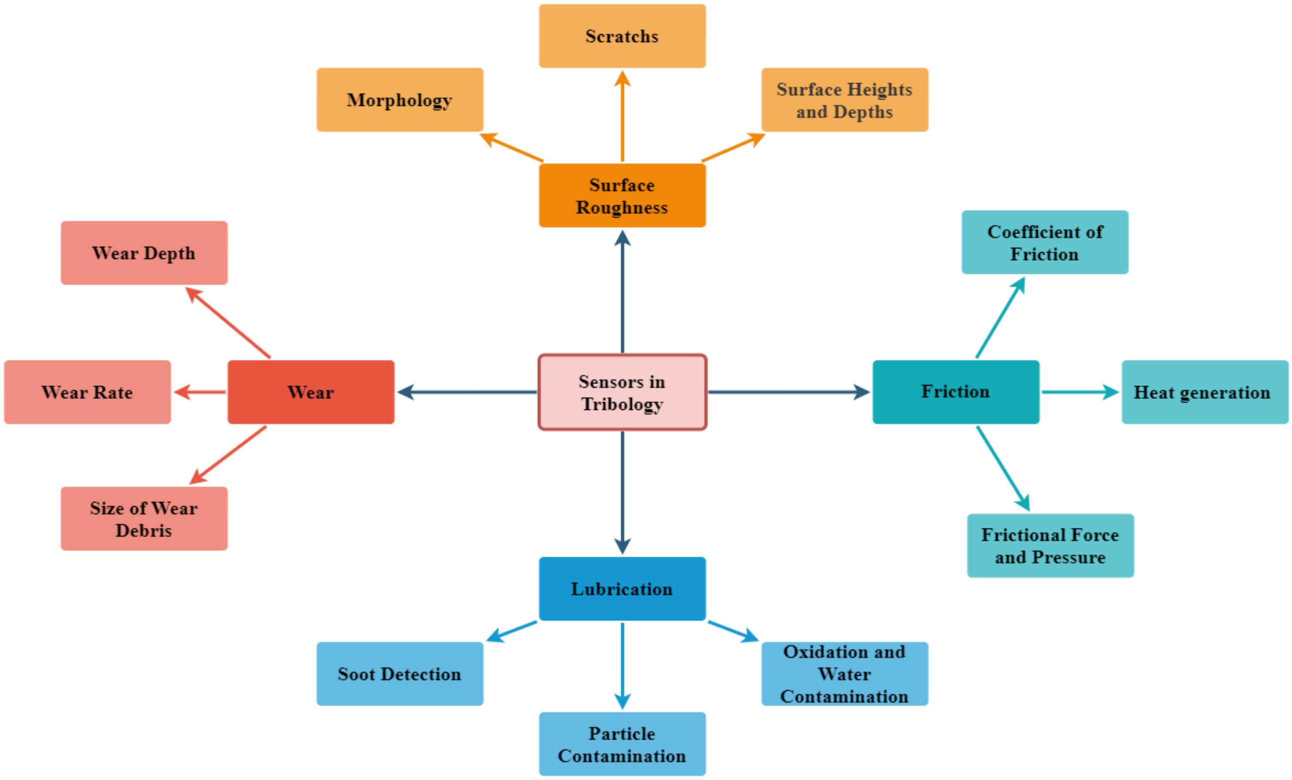

Figure 4: Sensors and various tribological domains

2.1. LUBRICATION AND SENSORS

Lubricant oil is one of main components of every machine to keep it properly working(Shafi, Raina and Haq, 2019)(Shafi, Raina and Haq, 2018) (Wani Khalid Shafi, Raina and Ul Haq, 2018). The prolonged use of the lubricant oil renders the oil unfit for use due to loss in the rheological, tribological and thermal properties of the lubricant. Moreover, the wear debris which gets trapped in the lubricant oil also deteriorates the properties of the oil(W.K. Shafi, Raina and Ul Haq, 2018). A good lubricant flow is necessary for temperature reduction, wear reduction and to keep the flow of material or particles due to material wear (Wang *et al.*, 2018). Oil monitoring is done by offline methods, which require experience in handling the equipment like ferrography and spectrometric analysis(Matsumoto, Tokunaga and Kawabata, 2016)(Guan *et al.*, 2011).

Online monitoring methods consist of techniques such as optical, photoelectric magnetic, inductive, capacitance, ultrasonic, electrical impedance, online X-ray spectroscopy and electro-static charge based techniques (Iwai *et al.*, 2010) (Kuo, Chiou and Lee, 1997) (Y. Wu *et al.*, 2016) (Hong *et al.*, 2015) (Minasamudram, Agarwal and Venkateswaran, 2013) (Appleby *et al.*, 2013) (Dingxin, Zheng and Jianwei, 2011) (Xu *et al.*, 2015) (Itomi *et al.*, 2006) (Kayani, 2009) (Powrie, 2000). Among the above-mentioned methods, capacitance based sensors are widely explored due to the simple design, thermal stability and non-contact measurement (Stevan *et al.*, 2015). The authors (Du and Zhe, 2011)(Wu *et al.*, 2013) give the advantages and disadvantages of all the above-mentioned sensors/methods. New methods involving hybrid sensor technology have been studied which involves the combination of capacitive, ultrasonic and inductive sensors to generate the hybrid model for the analysis of lubricant (Matsumoto, Tokunaga and Kawabata, 2016)(Appleby *et al.*, 2013). The sensors in a lubricant study can detect the wear debris, viscosity, moisture content, acidity and soot. The brief description about the nature of the operation of sensor and their job in the study is given in table 1.

Table 1: Brief description about the various types of sensors for lubrication and their mode of operation

Type of Sensor	**Methodology**	**Material, Change Detected/Size**	**Description**
Optical (Du *et al.*, 2013)	Debris morphology	Solid Debris/ 5-160µm	Difficult setup, gets affected by lubricant transparency.
Optical (Haiden *et al.*, 2015)	Dark Field Microscopy video setup	Metallic Debris/ 230 nm	Works on Brownian motion. Hence, with the decrease in viscosity, the tracking becomes easy.
Optical-Resistive (Sanga *et al.*, 2019)	quasi-digital sensor with opto-resistive technique	Change in Color/ From 0.5 to 8.0 (as per ASTM)	Detects the oxidation/contamination of the lubricant by change in color. Cost effective and high precision.
Optical (Pandreka, 2015)	Microfluidic counter	Ceramic beads/ 100µm	Detects the bacteria in the lubricant/fuel by photo-detector.
Capacitive (Raadnui and Kleesuwan, 2005)	relative variation of lubricant degradation	Ferrous Particles, Sio_2/ 100-120µm	Low cost, detects the failure at the early stage.
Capacitance (Liu *et al.*, 2000)	Dielectric constant with Bulk capacitance sensor	NA	Low sensitivity, water influence, large sensing zone
Capacitance (Shen *et al.*, 2016)	Microfluidic sensor	Metallic debris/ 0-40 µm	High sensitivity and low throughput
Capacitance (Nemarich, Whitesel and Sarkady, 1988)	Ultrasonic oil debris sensor	Solid debris/ Air Debris 170-1000µm	It can detect solid and air debris, but it cannot differentiate between metallic and non-metallic.

Ultrasonic (Xu *et al.*, 2015)	Change in Acoustic Amplitude with inductive sensors	Metallic, ceramic and air debris/ 50-310 μm	This system can differentiate between the Metallic, air and ceramic debris.

Further, the use of particular sensor depends upon the contamination to be detected and the parameter, which are perfect for detecting the impurity or contamination. The major parameters are particle count, viscosity, soot apart from total acid number (TAN) and the total base number (TBN), etc. The dependence of sensor selection on the performance parameter is shown in Table 2(Zhu, He and Bechhoefer, 2013).

Table 2: Dependence of sensor selection on lubricant performance parameters.

OIL DEGRADATION	PERFORMANCE PARAMETER	SENSOR REQUIRED
Water Contamination	Water Content	Viscosity Sensor
		Water in Oil Sensor
		Capacitor Sensor
	Viscosity	Viscosity Sensor
Particle Contamination Soot	Viscosity	Viscosity Sensor
	Wear Particle Count	Capacitor Sensor
		Conductivity Sensor
Particle Contamination Iron Content	Viscosity	Viscosity Sensor
	Wear Particle Count	Capacitor Sensor
		Conductivity Sensor
Oxidation	pH Measurement	pH Measurement
	TAN/BAN	Capacitor Sensor
		Conductivity Sensor
		Viscosity Sensor

Studies show that capacitor and viscosity sensors are the better among the others for the oil degradation studies and the operating maintenances of these sensors are low than the others (Zhu, He and Bechhoefer, 2013). In addition, the online monitoring of the data acquired from the kinematic viscosity and dielectric constant are easy to comprehend.

Traces of Cu^{2+} is normal in every lubricant oil but the with the increase in the concentration it can lead to mechanical failure, wear and increased the roughness the of the surface that was supposed to be smooth. Hence, the detection of Cu^{2+}ions is necessary to avoid the any mechanical and economical loss. The conventional methods to detect the metallic ions in the lubricant include spectrometry, Voltammetry, Atomic fluorescence spectrometry, Resonance scattering method, inductively coupled plasma-Mass spectrometry and colorimetric method (Kratzer *et al.*, 2014)

(Tyszczuk-Rotko *et al.*, 2016) (Kudr *et al.*, 2017) (Yang *et al.*, 2014) (Busa *et al.*, 2016) (Verma *et al.*, 2017). The mentioned methods are accurate and reliable but the equipment's involved in these methods are expensive and require extensive experience to detect the presence. Hence, the focus of researchers shifted towards the fluorescence-based probes are sensitive, reliable, and quick and can be employed for online metallic ion probe (Aydin, 2020) (Kong *et al.*, 2020). Until this date, the fluorescent probes coupled with carbon based quantum dots and semiconductor quantum dots have been widely used to detect the metallic ions or specifically Cu^{2+}in the lubricating oil (Milindanuth and Pisitsak, 2018) (Yu *et al.*, 2018) (Yan *et al.*, 2018). Recently, researchers have used the $CsPbBr_3$ perovskite quantum dots in the fluorescence probe to detect the presence of Cu^{2+} (Gao *et al.*, 2020). The device is highly sensitive ($8.62\mu M^{-1}$) and the detection limit up to 0.40nm. Generally, in fluorescence type of metal ion detection, Rhodamine B derivatives are used as probes (Yang *et al.*, 2016) (Biswal *et al.*, 2016). The rhomdamine are considered among the organic dyes, which have difficulty in achieving the stability (Medintz *et al.*, 2006). In comparison to this, fluorescent quantum dots have good resistance towards the light and the wavelength can be altered by change in size of the ion particle (Kadian and Manik, 2020).

2.2. Sensors and Surface Roughness

Tribology being a surface phenomenon, surface roughness is one of the important parameters for all studies pertaining to tribology. Surface roughness not only is an important parameter in determining the amount of friction and wear but also plays a crucial role in the lubricant entrapment and the wear debris. Moreover, surface roughness can help in understanding the wear mechanisms especially during the run-in stage.

Initially the surface roughness was measured with the probe type instrument known as stylus (Wang *et al.*, 1998). Stylus is the contact method and the sharp tip of the instrument may cause permanent scratch to the specimen, thus new optical methods were developed to which were non–contact in nature, which depend on the focusing, interference and speckle concepts. With further advancement in the field, TIS (Total Integrated System) based on diffused scattered light with colbenz sphere is used; the scattered light is then directed to the sensor for analysis (Harvey *et al.*, 2012). TIS is expensive, as it needs vacuum chamber to avoid dust.

With further advancements in the field, interference method is developed which uses fringe patterns developed from the two light waves with a significant phase difference, which is further analyzed by Michelson interferometer (Whitehouse, 2011). This method is very sensitive to vibrations and hence noise is produced in the interference patterns. The equipment is bulky and very difficult to handle. The speckle method is also one the famous methods in determining the RMS value of roughness by studying the speckles of contrast of the reflected light. The ratio for bright to dark (B/D) spots help in determining the surface roughness (Fujii and Asakura, 1974). Among the all the surface roughness methods, the microscopic methods remain the important ones. Generally, microscopic methods are categorized into types based on principal of operation; they are Scanning Tunneling Microscopy, and scanning probe microscopy. Further, with the integration of the electronics, the system becomes more sophisticated and easy to operate and analyze the data. Electronic Microscopic systems have sensors which either detect the reflection or the integrated back-scattered signals or the stereo effect (Bhushan, 2000). Table 3 shows the various types of sensors used in microscopes and the various associated aspects. Microscopy is critical in tribological systems with regard to checking the microstructure, grain structure, hardness indentation, wear scars, morphology of wear debris and wear mechanisms.

Table 3: Microscopy methods for measuring surface roughness

METHOD OF MICROSCOPY	TYPE	SENSOR	RESOLUTION SPATIAL	RESOLUTION VERTICAL	LIMITATION
Stereo-microscopy	Electronic	OFET Sensor	5	50	Single zooming system with small areas for scanning
Integration of back-scattered signal	Electronic	PDA 36A-EC	5	10-20	Requires conducting surfaces with hectic instrumentation
Stylus Instrument	--------	APS-C sensor	5-100	0.1-1	Damages specimen, slow measuring speed
Scanning tunneling microscopy	Optical	Electrochemical tunnelling sensors	0.2	0.02	Requires conducting surfaces with vacuum.
Atomic Force Microscopy	AFM	quartz tuning fork (QTF) force sensor	0.2-1	0.02	Tapping with the specimen remains the issue.

2.3. Sensors and Friction

Studying the methods of friction detection and measurement is very important for the development of in the areas involving contacts, just like vehicular dynamics, machinery for manufacturing industries, printing machines, stacking machines etc. (Haq and Anand, 2018a, 2019). Taking the case of metal forming in manufacturing industry where the friction is associated with high pressure due to rolling, the frictional forces and normal forces go hand in hand. Since the metal die interface have harsh environment, thus it is very difficult to calculate the normal force as well as the friction (Jeswiet, Arentoft and Henningsen, 2006). From the mathematical point of view, It was Karman (Alexander, 1972) who developed the model for rolling and the friction involved in it. Seibel and Pomp (Siebel and Pomp, 1929) were the first among the researchers to apply the principles of plastic working of metals for the rolling situation. Many other researchers attempted to highlight the work involving rolling and the friction phenomenon associated with it (Thomsen, Yang and Kobayashi, 1965)(Underwood, 1950).

For all the studies whether experimental or numerical, generally average values of friction were obtained, places with varying friction were ignored thus the need for sensors was felt. The first sensor for measuring forces in the metal forming and rolling was developed by Siebel and Lueg (Siebel and Lueg, 1933). It consisted of pin mounted on the work roll of rolling mill radially, which pressed down upon a load cell, which is mounted within the roll body. The main drawback of this sensor is that it could not measure frictional force, but the pin was later on used on every sensor for friction measurement. The pin sensor technique is remains the main and important way of determining the pressure and friction in the metals and metal composites. From the manufacturing point of view, the friction has been studied a lot in metal rolling processes(Anand *et al.*, 2020; Anand, Haq and Raina, 2020). MacGregor measured the contact pressure for metals (MacGregor and Palme, 1959). Pressure distributions in hot metal rolling has been studied using the pin technique (Yoneyama, 2017). Conditions for measuring the pressure in the metal rolling by pin setup has been investigated (Tozawa *et al.*, 1980). With further advancements in the domain, the multi-channel system was developed which could help in detecting the rolling pressure (Yoneyama, 2017). In cold metal rolling, pressure pin have used to detect the frictional stresses by oblique pin mechanism (Rooyen, 1957). Further this oblique pin mechanism has been used to detect the change in coefficient of friction using the contact arc method and length of arc method (Yoneyama, 2017). The same method was explored for checking the influence of parameters like strip tensions on the tangential shear stress and coefficient of friction in the roll gap due to oblique pin mechanism (Yoneyama, 2017). The friction sensors were studied more for better acquiring better data. In this regard, Researchers developed sensors for detecting and measuring the frictional stresses as well as pressure using the pin system along the 3D force detection system (YONEYAMA and HATAMURA, 1987) (YONEYAMA and HATAMURA, 1989).

Various other researchers conducted there experimentation in the same field in order to develop the sensors of pressure and friction measurement (Jeswiet and Nyahumwa, 1993) (Nyahumwa, 1996). These methods are unique and helpful in nature but there remains a problem, which is the gap between the pressure/detection pin and the hole in the tool. This can lead to leakage of deformed material. Apart from this, there lies the other problem of level between the sensor and the tool surface. It remains a challenge to keep them at the same level during the metal forming process. The researchers took this challenge and the novel sensor was developed using optical fiber displacement meter (Yoneyama *et al.*, 1994). With the advancement in the field more methods were developed. Strain-gauge sensors with a structure comprising an inner shaft and an outer tube connected at the tool surface and combined with a thin plate at the both ends (Yoneyama, 1999). These sensors came up to overcome the previous challenges. These sensors did not had the gap as that of the previous ones and the level difference between the tool and the sensor.

2.4. Sensors and Wear

Wear can be defined as the gradual removal of material from the surfaces, which are in contact with each other and are subjected to sliding on each other (Zmitrowicz, 2006). The wear is important parameter to define the mechanical failure of any component or material. Wear rate is one of the major factors for determining the life of any mechanical system. Thus to achieve the better mechanical and tribological systems, we need to have the better sensors and methods to detect the wear. The wear progression on any system or material is classified into three stages (Lu *et al.*, 2021). These are running in, steady state (stable) and end of life. In the running-in stage the contact is developed between the surface asperities and the plastic deformation of peaks/ tips is achieved which in turn flows between the tribo-pair also known as the wear debris. Steady state accounts for slow but constant wear debris production. This state is responsible for most of the machinery/operational life. As the quantity of debris starts increasing due to rolling, sliding, heavy loading etc., the rise in wear is seen and from which we can say that the system no longer functions properly, this phase is known as the end of life. Here the complete failure of the system is observed. Thus, a system is required, which can detect the wear at early stage and prevent the system failure. The wear has been studied a lot but there remains a problem in detecting the wear debris. As the wear debris size reduces in size or the number of debris particle is less, it is very difficult to sense them (Dwyer-Joyce, 1999) (Nilsson, Dwyer-Joyce and Olofsson, 2006).

Common methods of wear measurements are Scanning electron microscopy, 3-D profilometry, Scanning electron microscope, atomic force microscope. SEM cannot give the better picture of wear; hence, we prefer 3D profilometry for the better understanding about surface topography and wear. As the thirst of knowledge increases, the new methods for studying the problems also evolve. One of the technique is the development of in-situ tribotester (Wahl and Sawyer, 2008). In this method, a reciprocating tribotester was elevated on the white light scanning interferometer. With the advancement in sliding, the wear pattern was observed and a correlation model between the friction and wear was developed. For metallic surfaces, a 3D holographic microscope mounted on the pin-on-disk tribotester, which helped in detecting the changes during the experimentation (Korres and Dienwiebel, 2010). The main disadvantage of this method is that it works by employing radionuclide method, which is the cause for safety. To overcome the disadvantages of 3D holographic microscope, High precision 3D laser microscopy was developed and the wear analysis on nano-metric level was demonstrated (Park, Yang and Lee, 2015).

Related to industry, it is necessary to overcome the problems of tool wear in-order to increase the efficiency, quality and productivity. There are severe consequences, which can cost someone's life if the wear remains unchecked. Generally, the tool wear is detected by direct or indirect method. Direct method comprises of electrical resistance method and optical method. Indirect methods involve cutting force, vibration etc. Researchers have realised the direct methods are least important for wear measurement while are very useful as they develop the relationship between the tool wear and the signals from the signal during the tool operation (Siddhpura and Paurobally, 2013). For better monitoring and detection of wear, it is very important to develop the relationship from the various process parameters. Similar kind of work was done by the researchers and were the signals were obtained from the various sensors like accelerometer, force and acoustic emission for better tool monitoring during the milling process (Malekian, Park and Jun, 2009). Further, signals from acoustic emission and accelerometer were obtained from the sensors during the metal cutting process and correlation was established between the tool wear and the signal (Bhuiyan, Choudhury and Dahari, 2014). A unique method of combining the signals from the vibration sensors and employing the signal feature extraction for monitoring the tool wear. The above-mentioned literature is the proof that indirect methods are quit useful and effective in wear detection and monitoring, but there are certain disadvantages also, like the equipment is quite expensive, it's very difficult to difficult to process the signals. Cutting temperature for wear monitoring in the tools have also been useful. Recent work by researchers show that tool life can be enhanced by cooling effect and certainly can be employed as the wear measuring or detection technique (Y\ild\ir\im, 2019). some novel work related to sensors and wear measurement in important domains are shown in the Table 4:

Table 4 :Sensors for wear measurement in the various domains of tribology

Author	**Sensor Type**	**Domain**	**Description**
(Li *et al.*, 2021)	PCBN embedded thin-film thermocouple (TFTC)	Cutting operation	Sensor shows good dynamic response and effective in monitoring of tool wear by analyzing the tool cutting wear temperature.
(He *et al.*, 2021)	(PCBN) cutting tool embedded with a TFTC	Cutting operation	The research shows that cutting temperature is linked with the tool wear. Various cutting parameters have significant impact on the tool life. The proposed model learns from the signals obtained from temperature sensors, which help in better prediction of tool life.
(Y. Liu *et al.*, 2021)	Triboelectric Nanogenerator (TENG)	artificial prosthetics	A self-powered sensor TENG was developed to monitor and detect wear for artificial joints. This sensor is the result of thermo-compression fabrication process, was effective in detecting the wear debris in the

			artificial joints. Solid relationship was seen between the electrical signals generated and size of debris detected.
(Simon and Deivanathan, 2019)	Accelerometer (Vibration Sensor)	Drilling operation	The flank wear of tool in the drilling process is monitored by the vibration signals acquired in the accelerometer. The drilling is performed on ASI 316L steel with the high-speed steel. It has been observed that the amplitude of vibration decreases as the wear increases.
(Klocke *et al.*, 2019)	Acoustic Emission Sensor	Drilling operation	This paper deals with tool wear conditioning and estimation using the acoustic emission sensors. The fast Fourier transformation was used to analyze the signal.
(Jeong *et al.*, 2021)	Infrared Sensor	Drilling operation	Drill bit wear is monitored with infrared sensor which is the low cost method for predicting the wear. The drilling operation is performed on the titanium workpiece. The setup is easy to install and resistant to electromagnetic noise and the ambient temperature. The need for high performance signal analyzer is eliminated.
(Ramteke, Maddineni and Chelladurai, 2021)	Magneto-resistive Sensor	Piston Rings and Cylinder	The new model for detecting the running in wear has proposed in this paper. The combination of Magneto-resistive Sensor and permanent magnet helped in detecting wear. Apart from that, the results were compared with simulation results from the COMSOL Multiphysics 5.0. The comparison proved that this sensor has a potential to detect the wear. The correlation was developed between the magnetic field strength variation and weight loss, surface roughness and emission of engine.
(Wang *et al.*, 2020)	Piezoelectric ring	Bearing	Two types of sensors are used for the study, first one is the metal/piezoelectric ring transducers and second is the piezoelectric/metal ring transducers. The theoretical study model is prepared which is then compared with the experimental study. The study collects the signal as resonance and anti-resonance frequencies. The direct proportionality is seen in both the studies with resonance as well as anti-resonance

			frequencies i.e. the corrosion in pipes and wear in bearings.
(Tekkalmaz *et al.*, 2021)	Piezoelectric	Mechanical	The author presents the early wear detection technique assisted by electromechanical impedance method. The experimentation was performed on AISI 1040 Steel block. Some statistical techniques like Root Mean Square and Correlation Coefficient Deviation were helpful in detecting the location and depth of wear.

2.5.Sensors for Viscosity Measurement:

The Lubrication is an important aspect of tribology. The behavior of lubricant for different contacts and applications will surely affect the operation of machinery. Viscosity is one of the important parameters to check the health of lubricant; since it can vary with change is temperature and loading conditions. The change in viscosity can alter the process like fluid transportation from one end of the pipe to other, working of engine of any vehicle, any industrial machine which needs lubrication. Moreover, it can be used as the quality indicating parameter in food industries and petro-chemical industries (Postnov, Moller and Sosnovtseva, 2018) (Bista *et al.*, 2019) (Muñoz, Ancheyta and Castañeda, 2016). There are various conventional or basic methods for studying the viscosity like optical methods, capillary methods, and vibrational methods (Oh *et al.*, 2018)(Kurniati and others, 2018)(Webster and Eren, 2018). The optical fiber sensors are the advanced grade of conventional optical technology. This sensor has various advantages over the others like; they are of small size, almost zero electromagnetic interference, high sensitivity and lightweight (Idris *et al.*, 2020). Researchers have used quartz shear mode sensor for the measurement of viscosity of fluids (H. Wu *et al.*, 2016). With further advancements in the field, Sensors made up of poly-vinylidene fluoride (PVDF) with piezo- electric mechanism have been used to detect the viscosity of fluid. This method uses resonating frequency of PVDF and the quality response factor for viscosity measurement (Lu *et al.*, 2017). The method of resonating frequency has been further used with piezo-resonator disc radial mode for ultrasonic methods in viscosity determination (Purohit, Yadav and Jain, 2017). The researchers have also used gamma-configured optical fiber sensor for viscosity measurement (Yunus and Arifin, 2018). A new method involving the back scattering technology with optical coupler to detect the variations in the viscosity of fluid (Suhantoro and Yulianti, 2021). The ultrasonic sensors using the ultrasonic guides are among the attractive sensors because they can be used for high temperature and pressure applications. Researchers have used ultrasonic sensors using waveguides to detect and the changing viscosity of molten material, which are high temperature and pressure (Balasubramaniam *et al.*, 1999). Since, the wave guides are easy to customize therefore they can be used for wide range of applications. Researchers have used the torsional waves for detecting the liquid viscosity and density (Lynnworth, 1977). This work was extended by researchers for measuring the viscosity and density of liquid using the two wave-guides with rectangular and circular geometries (Kim and Bau, 1989). For high viscous fluids, researchers developed a sensor, which can detect the viscosity of the fluid using the aluminum wave-guides in a pipe (Kazys *et al.*, 2013). In a recent research related to ultrasonic sensors for viscosity measurement, authors reported the dipstick methods for the measurement of fluid properties such as viscosity and temperature. The study is the comparison between the ultrasonic properties of the wave-guides that are immersed inside the fluid to the ultrasonic properties of wave-guides that are immersed into the reference fluid (Huang *et al.*, 2021). In the present scenario, the conventional viscosity measurement is not required, as it requires a lot of time. Therefore, with the advent of industry 4.0, various online-based sensor systems were developed to specifically to detect the lubricant / fluid property. Some of the recent studies for online sensor studies are given in the Table 5.

Table 5:Recent studies on Online viscosity measurement

Author	Sensor-type	description
(Du, Wu and Cheng, 2015)	MEAS, Fluid Property Sensor (FPS)	The paper deals with the online methods of lubricant age detection. The parameters chosen are: dynamic viscosity, permittivity and wear particles.
(Bordoloi and Roy, 2021)	NTC thermistor, BTBMOF, IR transmitter and Receiver, MQ135 and MQ2 gas sensor, DHT 11.	The paper deals with the online lubricant condition monitoring. Among the five sensors mentioned, BTBMOF is used for viscosity measuring. The method proved effective to check the lubricant oil condition. The data was analyzed with fuzzy interference system using mamdani method.
(Wolak, Zaj\kac and Słowik, 2021)	mid-FTIR, Stabinger viscometer, microchannel viscometer, Ubbelohde Capillary viscometer	The paper aims to compare the kinematic viscosity of lubricant from four different sensors. It was seen that consistent results were only obtained for stabinger while as other were not precise.
(Z. Liu *et al.*, 2021)	WKAS	The paper deals with the condition monitoring of lubricant oil of intelligent aircraft engine. Various parameters were chosen for oil degradation and viscosity is one among those. The paper concludes by saying that, WKAS can be used for online condition monitoring.
(Sun, Liu and Tan, 2021)	microacoustic sensor	It has been seen that viscosity of micro based mineral oils can be measured by microacoustic sensor, however it cannot detect the effect of additives on the macroscopic viscosity.

2.6.Sensors in Cutting Tool Tribology

The study of tribology for cutting tool have evolved a lot in the past 100 years. Researchers putting an enormous amount of time for studying the wear of cutting tools in order to reduce the geometrical errors in the work piece. The irregular geometries of work piece are responsible for the malfunctioning of product, which further might be responsible for early maintenance cost, extra fuel consumption, lag in performance etc. Hence, it is necessary to get the accurate data related to the surface roughness and wear on the cutting tool for efficient machining. The various types of tool wear monitoring sensors are accelerometer, dynamometer, acoustic emission, and temperature sensor (Prasad and Babu, 2017) (Suárez *et al.*, 2019) (Kunto\uglu and Sa\uglam, 2019)(Scheffer *et al.*, 2003) . The above-mentioned sensors are indirect condition monitoring sensors. Tool health can be best analyzed by flank wear removal (Yan *et al.*, 1999). Recent studies have shown that vibration sensors also have the potential to detect the tool wear. However, there are some challenges also like the sensitivity of vibration signals due to the surrounding noise (Lauro *et al.*, 2014). The cutting process is responsible for generating acoustic emission signals. Due to its broadband criteria, it can help detecting the frictional forces and wear (Neslušan *et al.*, 2015). It has been observed that acoustic emission sensors have the ability to detect and oppose the catastrophic wear (Neslušan *et al.*, 2015). To understand the wear mechanism of cutting tool, various technologies like AI and ML have been employed. Researchers have used machine learning with the acoustic emission signals to predict the tool wear of aluminum ceramic composite with 10% SiC (Twardowski Pawełand Tabaszewski, Wiciak--Pikuła and Felusiak-Czyryca, 2021). The prediction error was seen to be less than 6%. Research has been done to compare the ability of five types of sensors in order to measure the tool wear. The signal obtained were due to the cutting forces, acoustic emission, temperature, current and vibration. Among the all types of signals/sensors, the AE and temperature proved to be efficient for wear prediction and detection (Kunto\uglu and Sa\uglam, 2021). In addition, AE has been employed to detect and measure the friction and wear in steel contacts under dry slip. It was concluded that RMS and AE energies integrated are the volume for wear provided the tribological or wear method remains constant (Geng, Puhan and Reddyhoff, 2019). Surface roughness can also be used for tool condition monitoring because it is continuously altered due to wear and friction. Researchers have shown the direct impact of surface roughness on the ultrasonic echo. Hence, it can be also used to detect the tool condition monitoring (Feng *et al.*, 2020). The cutting process is directly responsible for heat generation. The wear developed on the cutting tool also increases the temperature. So, the temperature-based sensors can also be used to detect the tool wear. The infrared based temperature sensors have studied thoroughly for their application of tool condition monitoring (Han *et al.*, 2020). Researchers have used temperature sensor TFTC for collecting the data from cutting tool. The TFTC sensor have been embedded into the cutting tool. The signals from the sensor have been used to predict the tool wear using SSAEs-BPNN model (He *et al.*, 2021). It has been observed that the tool tip temperature signal has high correlation with the tool wear. The tool temperature can be used to detect the early wear, alarm system and classify the wear stage during the cutting operation. Similar kind of research shows that the data can be better handled when it was treated with Mahalanobis-Taguchi System (Rizal *et al.*, 2017). This approach has the ability to analyze the data from the temperature sensors and classify the different tool-wear states in an abnormal group.

3. Tribology in the Light of Industry 4.0

The term "Industry 4.0" is the technical representation of fourth industrial revolution (Kamble, Gunasekaran and Gawankar, 2018)(Jandyal *et al.*, 2021). With the advent of industry 4.0, there has been significant increase in the automation of manufacturing system, efficient sensors for diagnostics and enhancement in the information transmission system. The industry 4.0 promises enhancement in productivity with the reduction in production cost. Most important concept of industry 4.0 is the "Smart industry" where everything is interconnected with each other and where the human robot interaction is enabled. The industry 4.0 encourages amalgamation of sensors, communication system and internet. It has nine fundamental pillars which include advanced robotics, 3D Printing, augmented reality, simulation, horizontal/vertical integration, internet of things, cloud computing, cyber security and big data and analytics. The tribology has a strong dependence on the industrial revolution.

With the advent of new manufacturing era, new tribological challenges have been developed which need to be solved with modern methods and techniques. For any industrial equipment, its design and working can have a significant influence over the wear and friction, hence on their performance and reliability. Monitoring of wear and friction by studying the parameters like temperature, vibration can help in detecting and predicting the equipment failure. New sensors for bio tribology, green tribology pave the way for the betterment of human life and low carbon emission. Cyber-physical system and AI are the important components of industry 4.0. And have contributed and enhanced the tribological research any many ways. Separate sections for cyber physical systems and AI/ML are included below in accordance with the tribological studies:

3.1. Tribology and Cyber-Physical System

Tribology has played a well-known role in the field of maintenance and diagnostics. To reduce the cost of working and to avoid the failures in any mechanical system, it is necessary to operate the machine within the fixed parameters and run the early diagnostics. From the recent literature survey, it is very evident that tribology has done a lot in predicting and diagnosing the faults in bearing division of materials and mechanical engineering (Randall, 2004)(Yu, Cheng and Yang, 2005)(Elasha *et al.*, 2015). The work in this field has been extended using the cyber-physical field systems, commonly known as "Tribology 4.0" (Glavatskih and Höglund, 2008). This field is the integration of sensors with the internet hence providing the real-time data and converting the off-line sensors into the on-lines ones, hence predicting the wear and online monitoring is achieved (Randall, 2016) (Marklund, 2017). Cyber physical system is the amalgamation of embedded system with the physical system. The system has computation, communication and control capabilities. These triple 'C' Capabilities give the system autonomy to detect, predict and communicate the data with the user in the least possible time. The Cyber Physical System uses the AI to acquire the information of real time environment.

The vein diagram showing the combination of sensors with cyber-physical system and conventional tribology in order to acquire real-time data is shown in Figure 5. Oil analysis has also been a popular method to determine the wear and lubrication in the friction/tribological pairs (Marklund, 2017). The various methods to check the oil condition are ferrography, spectrum and some methods of chemical technology (Wu *et al.*, 2008)(Elnasharty *et al.*, 2011)(Idros, Ali and Islam, 2014). Surely online methods are better way to determine the oil condition. Various online oil viscosity measurement techniques are acoustic-vibration measurement, quartz-resonant, capillary and micro vibration method (Agoston, Ötsch and Jakoby, 2005)(Markova *et al.*, 2011)(Durdag, 2008)(Stoyanov and Grimes, 2000). To detect the chemical changes in the oil caused by the contamination is done by capacitance and impedance methods (Raadnui and Kleesuwan, 2005)(Turner and Austin, 2003). The wear in the tribo-pair which gets into the oil is detected by photo-electric sensor, combination of photoelectric and magnetic sensor, inductance sensor and the sensors based on capacitance and ultrasonic methods (Kwon *et al.*, 2000)(Kuo, Chiou and Lee, 1997)(Wu *et al.*, 2009)(Han, Hong and Wang, 2011)(Edmonds, Resner and Shkarlet, 2000).

Some other online methods to check the wear of material are: infrared (IR) and Fourier transform infrared (FTIR) spectrometry (Adams, Romeo and Rawson, 2007), XRF (X-ray fluorescence) sensors (de Voort, Sedman and Pinchuk, 2011), photo-acoustic spectroscopy (PAS) (Koskinen *et al.*, 2006), fluorescence spectroscopy (Becker, 2008). Research has been done to develop the methods online-based sensor monitor for detecting the wear (Chiou, Lee and Tsai, 1998), which works on the principal of electromagnetic flow. Also for the marine based diesel engine, study has performed and the new online method for detecting the ferromagnetic materials in the oil, which can help in detecting the quality of engine-oil (Liu *et al.*, 2000).

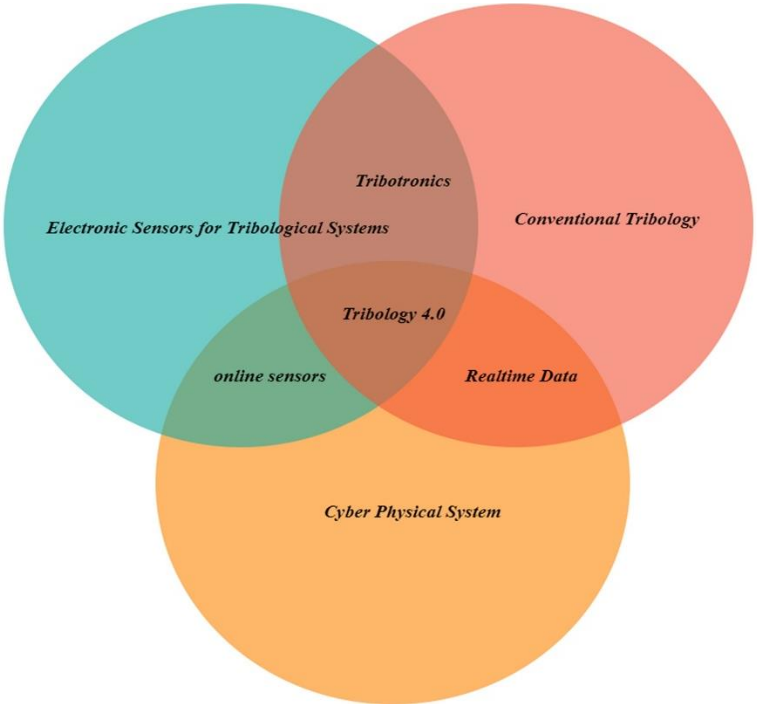

Figure 5: Vein diagram between the sensors, conventional tribology and the cyber-physical system

3.2. Tribology with AI and ML

In the recent years, lot of work has been done to in the field of AI and Tribology. ML and deep learning models have been employed to enhance the tribological properties of materials (Rosenkranz *et al.*, 2021). It all started in 1998, when artificial neural network was applied on the data points obtained from the lubricated ball on disk sliding experiment and microscopy (Umeda, Sugimura and Yamamoto, 1998). The relationship was successfully between the experimental conditions and the obtained particle feature. Thus, by this algorithm, the particle feature could be predicted and hence the condition monitoring. Soon after that, researchers applied the two algorithms, which were trained with vibration input signals for condition monitoring in ball bearing (Subrahmanyam and Sujatha, 1997). For journal bearings, researchers have used ANN based convolution neural network with acoustic emission signals to characterize the bearing condition into the three zones; running –in, insufficient lubrication and particle contamination (König *et al.*, 2021). This algorithm worked with the accuracy of 97% and the sensitivity of 100%. The AI and ML can be regarded as disruptive technologies in field of science and engineering. It has found its relevance almost every field. For material science and tribology, the field of AI and ML have been exploited a lot and have solved almost every difficult problem in this domain. Since, every tribological process be it wear, friction, are the time dependent irreversible process where every data point comes with the material loss. The block diagram of AI enabled sensor system for tribological studies is shown in Figure 6.

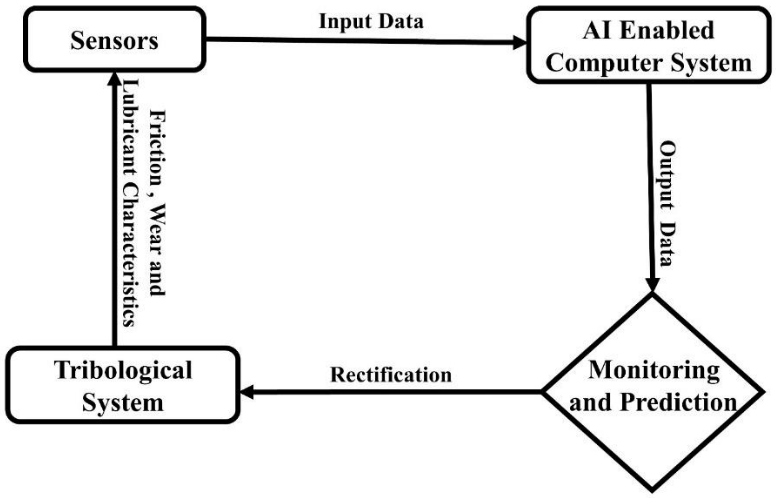

Figure 6: AI enabled sensor system for predicting and monitoring tribological properties

Here the importance of AI and ML techniques pave a way for new advancements by reducing the time, providing mathematical model and predicting the wear, friction, wear depth etc. Some important work in the related to Tribology and the AI/ML models involved are shown in Table 6.

Table 6: Recent work in AI/ML for predicting various tribological properties

Author	ML/AI Model	Operation	Domain	Parameters Predicted
(Egala, Jagadeesh and Setti, 2021)	ANN and Linear Regression model	Flat Pin on disk Tribometer	Short Castor Oil Fibre	wear, interfacial heat, and COF
(Cetinel, 2012)	Back propagation ANN	Pin on disk tribometer	thermally sprayed Al2O3 -TiO2 coatings	linear wear, COF
Sahraoui et.al (Sahraoui *et al.*, 2004)	back propagation ANN	Pin on disk tribometer	HVOF sprayed Cr-C-Ni-Cr and WC-Co coatings and electroplated hard chromium	COF
(Upadhyay and Kumaraswamidhas, 2016)	back propagation ANN	Pin on disk tribometer	multilayer nitride PVD coatings	wear rate, COF
(Boidi *et al.*, 2020)	Hardy multiquadric RBF	mini traction machine	surface texture design for EHL contacts	COF

(Durak, Salman and Kurbano\uglu, 2008)	back propagation ANN	Journal bearing test rig	PTFE-based additives in mineral oil	COF
(Humelnicu, Ciortan and Amortila, 2019)	back propagation ANN	pin-on-disk	vegetable oil-diesel (Mixture)	COF
(Bhaumik, Mathew and Datta, 2019)	feed forward ANN	four-ball-tests	Blend of coconut, castor and palm oil with friction modifiers (MWCNT and graphene)	COF
(Baboukani *et al.*, 2020)	Bayesian modeling	Sliding test	Graphene and transition metal dichalcogenide	maximum energy barriers
(Argatov and Chai, 2021)	Multi-Layer Perceptron	Sliding Test	Inconel 600 alloy, aluminum alloy matrix composites	Wear Coefficient, Specific wear rate
(Kristipadu and Lawrence, 2021)	Regression method, Support Vector Machine, Decision Tree method, LSTM	linearly reciprocating tribometer	Low Carbon Steel	COF

Table 6 shows the recent developments in the field of tribology and AL/ML. It is said that AL/ML techniques are bit complex, need certain expertise but in the end, they help in saving the precious time resources. Mostly, tribological problems are non-linear in nature, which makes AI and ML more suitable for the analysis. From COF to wear and material composition, the tribology has been expanded. With the development of new algorithms, The AI makes it easy to predict the tribological properties of materials and predict the future result, helps to create the best composition of material/Nano-additive for the particular application. Besides this, In future AI and ML can be used in deciding the size of Nano-particles for enhancing the lubrication, reducing friction and wear.

The paper shall help tribologists and industrialists to relate the various aspects of tribology with the various pillars of Industry 4.0 and help to devise tribological systems with improved efficiency. Also, the area of sensors can be further developed in respect of Industry 4.0 keeping in view the tribological applications.

4. Limitations

The current study does not focus on the aspects such as coatings, surface treatments, advanced materials and environments which affect the friction and wear. The paper only relates the basic parameters of tribology. The paper also does not include the issues regarding reliability of data and repeatability of the data. The paper also does not focus on tribological systems which have an interface with biological systems.

5. Conclusions and Recommendations

The complexity and interdisciplinarity nature of the field of tribology, an important aspect of various engineering equipment, implementation of various principles of industry 4.0 would not be possible without augmenting the various parameters important from tribological point of view with various pillars of Industry 4.0. The various concepts of industry 4.0 such as Artificial Intelligence (AI), Machine Learning (ML) and Internet of Things (IoT) can be augmented with various tribological systems by developing smart sensing technologies which will enable the end users to monitor the various parameters such as friction, wear and lubricant performance. The quest for minimizing human intervention in operating and maintaining tribological systems is possible only by interconnecting various tribological systems and collecting and sharing data. The data is important for monitoring and remote operation of engineering systems. Data pertaining to the various parameters critical from tribological point of view such as coefficient of friction, wear rate, temperature, humidity, contact pressure and surface characteristics obtained by using advanced sensors can be helpful in implementing various pillars of Industry 4.0 in tribology related industries. Determining the health of machinery and carrying out the maintenance of machinery particularly exposed to extreme environments shall become easier, cost effective and efficient by employing the augmented approach. The various applications areas include defence, marine(offshore), space, high altitude monitoring and operation of engineering systems. A deeper understandings of the concepts of tribology and Industry 4.0 is needed to implement industry 4.0 in tribological systems.

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