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Advancing Surface Engineering for Tribology: From Functionality to Connectivity

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Surface functionality plays a pivotal role in Tribology, a discipline dedicated to examining the interactions of surfaces in relative motion. The approach, known as Tribotronics, combines Tribology and electronics, enabling active tribological components to be embedded in larger systems and networks constituting the Industrial Internet of Things. Leveraging novel technologies such as advanced sensing coatings and triboelectric nanogenerators, the sensing capability of Tribotronic systems undergoes a transformative shift from a device-centric to a surface-centric paradigm. This critical advancement unlocks the potential for direct interface probing and in-situ measurement of tribological processes, marking a significant milestone in the field. This emerging trend introduces the concept of the Internet of Surfaces, a novel perspective within surface engineering. It entails the amalgamation of sensing capabilities, embedded power generation, and external analytics, creating dynamic materials in the context of Industry 4.0.

Surfaces define the boundaries in the world of materials, where functional processes such as absorption, reflection, corrosion, insulation, and friction take place. However, the functionality of engineered surfaces has been one-dimensional (1D), making them less relevant for the digital world.

Surface engineering, as a branch of materials science and engineering, focuses on modifying the surface functionality of materials while preserving their bulk properties.[1] Fueled by the first two industrial revolutions, surface engineering enabled a more efficient use of materials, with research and development efforts primarily centered on enhancing specific surface functions, e.g., stickiness,[2] slipperiness,[3] or self-cleaning.[4] One area where surface functionality is essential is Tribology, the scientific study of friction, wear, and lubrication of surfaces in relative motion.[5] It involves investigating the interactions between solid surfaces, as well as the fluids and materials used to reduce friction and wear. Tribology has a broad range of applications in engineering, materials science, physics, chemistry, and biomechanics. It is essential for designing and optimizing the performance of machinery, reducing energy consumption, improving product durability, and minimizing the environmental impact of wear.

With the wider availability of reliable sensing technology, tribological components such as bearings, shafts, and gears are being connected for real-time data acquisition.[6] The data collected by these sensors are analyzed using machine learning algorithms to identify patterns, detect anomalies, and predict failures before they occur. Maintenance personnel can take proactive measures, such as adding lubrication or replacing worn parts, to prevent unplanned downtime and costly repairs. This trend, called Tribotronics, involves the integration of Tribology and electronics to form smart active tribological systems, which utilize modelling, sensors, and actuators to dramatically improve performance.[7]

The concept of Tribotronics is enabling the tribological components to be embedded in larger systems and networks constituting the Industrial Internet of Things (IIoT). The IIoT is a subcategory of the Internet of Things (IoT) that focuses on the use of connected devices and sensors in industrial settings.[8] While both IoT and IIoT involve connecting physical objects to the internet to collect and exchange data, the main difference lies in their respective applications. IoT generally focuses on consumer-oriented applications, such as smart homes and wearables, while IIoT focuses on optimizing industrial processes and equipment. Additionally, IIoT typically involves more advanced technologies, such as artificial intelligence and machine learning, to manage and analyze the large amounts of data generated by industrial devices.

Within the context of materials in the IIoT systems, the challenge is to shift the sensing capability from a device (e.g., gearbox) to its components surface (gears and shafts). If successful, it would allow probing the interface directly and measuring the tribological processes in situ, rather than relying on so-called "loss outputs" such as vibration as indirect feedback data. This is an exciting new trend in surface engineering, which can be enabled by two key scientific developments: 1) sensing coatings and 2) triboelectric nanogenerators (TENGs).

Sensing coatings are designed to detect and respond to changes in the environment, such as temperature, humidity,

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pH, pressure, or the presence of a specific gas or chemical.[9] Sensing coatings typically contain a chemical or biological component acting as an active agent. The sensing material is embedded or coated, and it undergoes a change in its physical or chemical properties when exposed to a specific stimulus. The response of the sensing coating can be measured through changes in color, fluorescence, or electrical conductivity. This information can then be transmitted to a monitoring device to provide real-time information about the environment. The principle behind the second concept, TENG, is based on the triboelectric effect, in which the generation of an electric charge occurs when two materials with different electronegativities come into contact and then separate.[10] TENGs can be designed in various shapes and configurations, including thin films, and can be integrated into the sensing coating. There have been already attempts to incorporate both self-powering and self-sensing capabilities in one tribological system.[11] A rolling bearing called triboelectric rolling ball bearing was developed, using a TENG with flexible electrodes on its outer ring. During bearing rotation, an electricity is generated through contact electrification between rolling balls and the ring. The rotating speed sensing is achieved by measuring the magnitude and frequency of the output current rather than a proprietary coating in this case.

By combining sensory and self-powered capabilities within surfaces, the digital connectivity can be shifted from a device to a surface, a crucial step toward the concept that I would call the Internet of Surfaces (IoS). The IoS term recognizes the role of surfaces in the digital world, similar to how the IoT and IIoT realizes the opportunities from connectivity of physical devices. For example, by implementing the IoS principles in systems like wind turbines, we would observe a transition from measuring the secondary indirect signals like noise and vibrations, to directly probing the primary signal simultaneously at all tribological interfaces including gears, slip rings, wings, and several types of bearings.[12] The maintenance strategy based on the signal processing and decision-making analytics would remain the same, but the quality of the signal feeding into the algorithms will increase dramatically **Figure 1**.

The IoS can be further described in the context of different types of load-bearing surfaces, both manmade and natural, based on their key characteristics. The road map presented in **Table 1** provides examples ranging from a basic component, such as a metal implant, to a connected surface that forms part of the IoS. There are notable similarities between the IIoT and IoS systems, as they share fundamental principles and rely on existing technology for data transmission, communication, and data

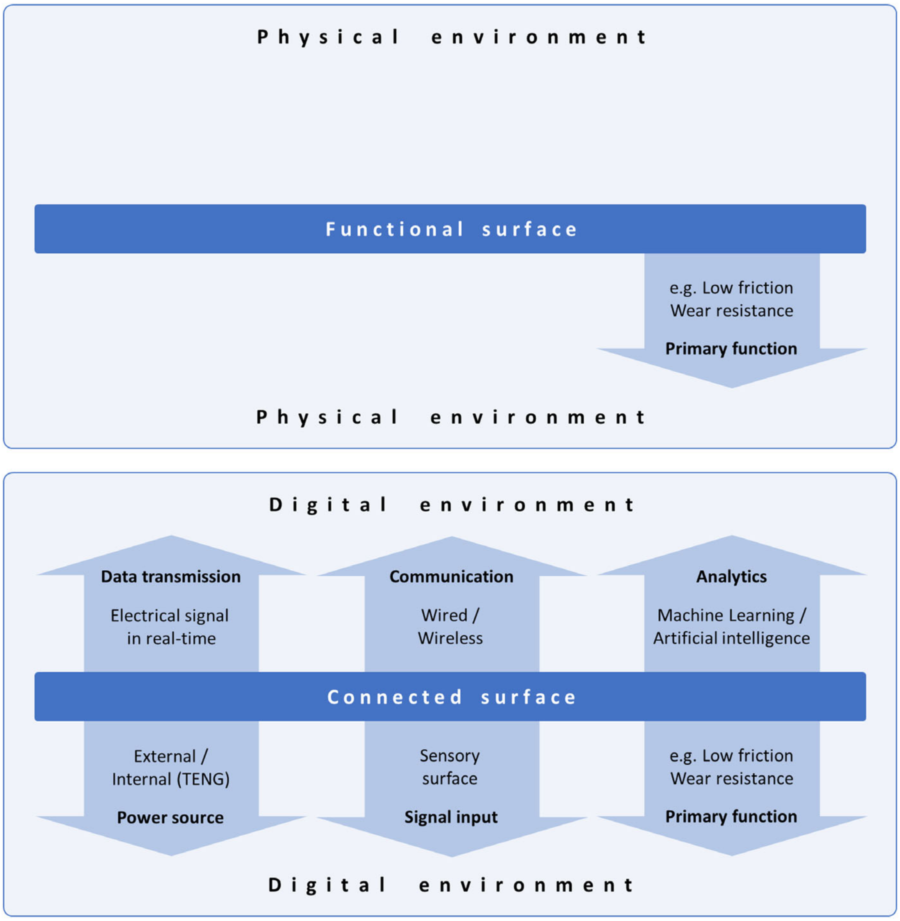

Figure 1. Attributes of functional and connected surfaces. In a physical environment, information is typically represented in continuous, nonbinary forms, such as physical objects fulfilling specific 1D function. In contrast, in a digital environment, information is represented in discrete, binary values and can be processed electronically, allowing for integration with IoT and IIoT systems, and ultimately enabling the IoS concept.

Table 1. The Internet of Surfaces on a spectrum of manmade and nature-made load-bearing surfaces.

	Manmade passive component	Connected device (Industrial Internet of Things)	Connected surface (Internet of Surfaces)	Nature-made system
Example	Knee implant	Integrated sensor ball bearing	*Nonexistent*	Synovial joint
Data transmission	None	Electrical signal in real time		Chemical signal in real-time
Communication	None	Wired/wireless		Neurons
Processing and analytics	None	Artificial intelligence/machine learning		Brain
Power source	None	External (wired/wireless)	External/internal (wired/wireless/TENG)	Internal (nutrients)
Signal input	None	Sensory device	Sensory surface (sensing coating)	(biological tissue)

processing and analytics. The difference lies in the source of the input signal and the method of energy generation.

Beyond connectivity, the integration of in situ adjustable properties into tribological surfaces will create new active machine elements that have traditionally been passive. Stimuli-responsive surfaces are those that exhibit defined and reversible changes in physical properties when exposed to external triggers. These surfaces offer opportunities for interactive materials that can adapt to demands, sense their environment, and act autonomously.[13] The choice of the stimulus depends on material characteristics, the desired surface property change, and application requirements. Electrically triggered activation is particularly attractive due to its rapid response and the ability to create multiple individually addressable switchable regions on a single surface.[14]

It is worth recognizing the important role of green materials and biomaterials and the way they are transforming surface chemistry and engineering by offering sustainable, biocompatible, and environmentally friendly alternatives to traditional materials.[15] Their use reduces the environmental footprint, enhances biocompatibility, and promotes sustainability across various industries, including medical applications and packaging. Innovations driven by green chemistry are leading to novel surface functionalization methods. These materials will be pivotal in advancing eco-friendly technologies and reducing the reliance on nonrenewable resources in surface engineering.

In conclusion, the journey from physical functionality to digital connectivity in surface engineering represents an exciting frontier in materials science and technology. Combining sensing surfaces with embedded power generation and external analytics will create a scenario in which machine elements are digitally integrated into the operational environment. The term IoS captures the nature of that trend and positions materials within a wider context of Industry 4.0 and associated IIoT. It gives a new dimension to the traditional functional surfaces, making them an integral part of a bigger connected system. It has the potential to revolutionize the way we interact with and utilize materials in a wide range of applications, leading to innovative products and systems that are more efficient, sustainable, and adaptable to the needs of our interconnected world.

Conflict of Interest

The author declares no conflict of interest.

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industry 4.0, sensory surfaces, surface engineering, tribology

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