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Friction

Review Article

Tribotronic components: A revolution transforming machine elements into cyber-physical systems

Ian Sherrington[1,2,✉], Sergei Glavatskih[2,3,4]

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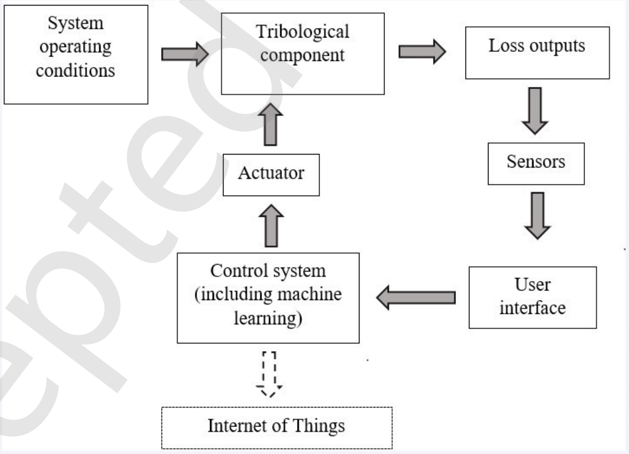
ABSTRACT: This paper explores the development of a subject called "tribotronics", the science of actively controlled tribological elements, and considers the potential of tribotronics as part of a revolutionary machine element design for the future. It presents a "state-of-the-art" assessment of some devices that can be considered "tribotronic" and are currently in common use, as well as a review of examples of recent progress in research in tribotronics. It also presents a "perspective" on the future challenges and likely developments in the subject, including the integration of tribotronics with developments in other fields of digital technology, such as Industry 4.0, the "Internet of Things (IoT)", and machine learning (ML), potentially leading to "cyber tribotronic systems". In conclusion, tribotronics will contribute significantly to transforming the design of the components and machines of the present day into cyber-physical systems in the future.



KEYWORDS: tribotechnology; tribotronics; active tribology

1 Introduction

The historical development of humankind can be summarized in many ways. One way is to view it through its technological achievements. The most significant developments in the technical capabilities of society are often transformative, profoundly influencing the behavior of individuals and their effects on the local and global environments. The ancient developmental stages included "stone age" and "bronze age". More recent developments are often referred to as "industrial revolutions". Histories recognize three "industrial revolutions"; the precise interpretation, and dates for these industrial revolutions vary, but they can be summarized as follows.

- The first industrial revolution, "mechanization", took place from about 1765, and involved the transition from hand production of goods to production by machines.
- The second industrial revolution, which started in approximately 1850, was characterized by the development of mass production methods and the widespread use of metals, especially steel, as well as chemicals, including gas and oil, as people realized that the mass use of machines in factories was a highly efficient way to manufacture goods to a higher standard for an increasing population.
- The third industrial revolution started during the 1950s, and involved elements such as electronics, nuclear capability, and biotechnology.

Recently, the World Economic Forum recognized a fourth industrial revolution [1], commonly referred to in Europe as Industry 4.0, which involves the emergence of the connectivity of computing systems, the development of the internet, the widespread use of sensors, etc. Some individuals believe that this will rapidly evolve into a fifth industrial revolution, involving the extensive use of artificial intelligence, the personalization of goods, collaborative robotics, the use of big data, etc., supporting a "superintelligent society", a concept referred to by the Japanese government as "Society 5.0" [2].

Ciulli [3] reviewed the development of tribology in the context of industrial revolutions, highlighting the main developments in each industrial revolution. He has also discussed the potential contributions of tribology to Industry 4.0 and (indirectly) Society 5.0. In this paper, these authors extend that discussion in the

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[1] Jost Institute for Tribotechnology, University of Central Lancashire, Preston PR1 2HE, UK. [2] System and Component Design, KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden. [3] Department of Electromechanical, Systems and Metal Engineering, Ghent University, Ghent B-9052, Belgium. [4] School of Chemistry, University of New South Wales, Sydney NSW 2052, Australia.

✉ Corresponding author. E-mail: isherrington@uclan.ac.uk

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specific context of feedback-controlled tribological components (tribotronics).

2 Contextualizing the role of tribology

Currently, technological changes are taking place against emerging challenges. The most notable of these challenges is the aim of developing a globally sustainable future, which includes the goals of arresting and reversing climate change and environmental damage [4]. This goal involves many social and technical challenges. The technical challenges involve better management of materials and production processes, increased use of clean energy, more effective use of materials, and reduced gaseous, particulate, and fluid-based emissions.

Tribology was defined as the science and technology of "surfaces in relative motion". In the mid-1960s, the application of good tribological principles was initially recognized as playing a central role in maintaining the economic viability of machines [5]. Soon after this, in the 1970s, the price of energy increased dramatically, and the use of good practices in tribology also became recognized as playing a significant role in energy conservation [6]. Most recently, in the early 2000s, the application of sound tribological principles in all stages of the design, use, and disposal of machines was recognized as a critical element in design optimization to manage the sustainability of machines [7]. Approximately 100 EJs of energy are consumed annually to overcome friction, approximately 20% of the energy produced globally [8]. However, demonstrating the value of good practice in tribology, it has also been reported that in the road transport sector alone, approximately 17.5% of the energy used could be saved by applying effective new tribological solutions [8].

It is clear that efficient machines make effective use of energy supplies, and machines with low wear have a long life, which reduces the waste of material and maintenance costs. Both reducing energy consumption and extending component lifetime are critical elements in sustainability, lowering the carbon footprint of a device and contributing to reducing climate change. For example, CO_2 emissions should be reduced to reduce global warming.

Traditional tribological design has focused on friction and wear reduction through passive approaches. These include, for example, the development of new or improved materials, the use of surface coatings/lubricant formulations/additives, the improvements in surface finish, and the reductions in manufacturing tolerances. Consequently, improvements in the performance of tribological machine elements over the last few decades have been limited to incremental developments related mainly to these factors. It appears, however, that this incremental progress slows down with time. As an example, Glavatskih and Höglund [9] discussed how the mass of a (specific brand of) rolling element bearing, with a given load-carrying capacity, has steadily changed over recent decades. They show that more recent improvements in the ratio of bearing mass to load capacity tend to be smaller than those achieved in the past, suggesting that future improvements in materials may not continue to yield such significant weight/performance savings. This is evidence that at least one very widely used tribological component is approaching the end of its design evolution curve [10]. It is likely that other components will also reach this position. Consequently, it can be argued that a transformational "step change" is required to make significant enhancements in the future.

Current tribological devices generally operate without feedback on their operating state or their physical condition. Consequently, most lubricated bearings, gears, and seals are unable to modify their own state to optimize their performance or to compensate for developing issues, for example, to operate at maximum efficiency, to respond if they have been lubricated using an incorrect fluid, or to compensate for their operation owing to changes in shape due to excessive wear. Therefore, one approach remaining to be explored is the use of actively controlled tribological components (or systems) whose operating state can be adjusted in response to sensor feedback. A new term, "tribotronics", has been coined to describe the technology of active tribological machine components [9].

Allowing passive devices to evolve to become sensory and respond actively generates the opportunity for a step change in performance as well as the ability to meet new and distinct demands, which will be posed by the development and use of more autonomous machines. We live in a time where technology is evolving ever more rapidly and where several embryonic technologies seem likely to contribute to the rapid development of disruptive new designs of machine elements. These include the development of microsensors for tribological measurements [11], smart materials [12], biomimetics for tribology [13], machine learning (ML) and embedded intelligence [14, 15], additive manufacturing (AM) [16], internet connectivity and the IoT [17], and energy harvesting [18]. AM, in particular, has the potential to considerably influence the design of tribotronic devices. AM can enable manufacturing with minimal waste, and using "design for manufacture" concepts, it also allows the construction of novel mesostructures that allow the integration of sensors, actuators, and electrical circuits within machine components in "one-step manufacture", potentially giving rise to the evolution of new, as yet unforeseen, devices. Given the prevailing technological developments and the demands of future technology, it seems that actively controlled tribological components and systems are not only entirely feasible but also inevitable developments in future products and machines.

Many types of new autonomous, semiautonomous, or remotely operating machines are in use or under development. Some of these are conventional machines, such as wind turbines, and some are less conventional, perhaps partially or completely replacing the capabilities of humans in various forms of robots or assistive "cobots". For example, assistive surgical robots and unmanned vehicles have been used. Regardless of the current form of a machine, over time, it will likely become more autonomous, and many mechanical systems and components will be integrated with electrical systems involving algorithmic machine intelligence and "IoT" connectivity to form an arrangement commonly referred to as a "cyber-physical" system.

A tribotronic component or system with connectivity can be seen as part of the fourth industrial revolution. However, a tribotronic device with some form of machine intelligence and autonomy can be part of a cyber-physical system employing "big data" to support learning and intelligent, interactive network operation. Consequently, devices of this form are part of the next generation of tribotronic components/systems, which are likely to evolve in the longer term. We coin the term "cyber tribological system (CTS)" here to describe these devices.

The emergence of cyber-physical systems is generally perceived to be an increasing norm for engineering products, and this also has considerable implications for the future of tribology. To date, developments in autonomous machines have focused on developing their ability to complete a functional task. However, as they become increasingly autonomous, these machines benefit significantly from being self-regulating and able to adapt to dynamically manage their own capabilities and respond under changing operating conditions. This includes adapting to load, stability, thermal expansion, etc., as a well as self-diagnosing and managing faults, conducting prognostic analyses of faults, and generally offering increased levels of self-maintainability to realize operational goals and safe operation. Consequently, traditional tribological systems and components are also inevitably set to become cyber-physical subsystems.

Systems that are currently monitored through online methods probably offer the greatest opportunity to be part of a cyber tribotronic system. Their ability to function as part of the IoT is an integral element that enhances their functional capability. The integration of sensors with the IoT is now a routine step, and battery-driven development kits [19] are available to support the detection of faults for IoT-based condition monitoring systems, which incorporate low-power consumption microelectromechanical sensors (MEMSs) and secure wireless communication.

Scenarios for IoT-based components that can address significant tribology issues are relatively easy to envision. For example, if a wind turbine array fitted with CTS bearings was subjected to a potentially damaging adverse wind gust, the first turbine in the array to be met by the wind gust would be able to detect the gust and communicate an alarm condition to other bearings in the array electronically, permitting them to respond to prevent damage or adverse operation. This could be achieved by arranging them to rapidly "feather" to reduce the likelihood of damage due to adverse wind gusts. Another simple example could be a self-delivery drone. Many companies see drones as plausible delivery tools, but their failure, perhaps through a bearing fault in a rotor system, gives rise to significant safety concerns if drones fall into populated areas. Thousands of drones cannot be inspected by maintenance engineers. Therefore, rotor bearings with adaptable fault diagnosis/prognosis, IoT communication capability, and ML algorithms for control and emergency running characteristics could become the norm.

3 What is a tribotronic system?

Many tribological components, such as bearings and seals, operate via passive self-adjustment. That is, they have a dynamic response on the basis of the physics of their design, but this response cannot be changed following design and installation, and the (same) response is always determined by the same operating conditions. Sometimes these components have some form of condition monitoring system, but no feedback other than maintenance by a human is possible. A conventional tribological component such as this can be represented in Fig. 1.

In contrast, a tribotronic system can offer a range of operating states for any given operating condition. A schematic diagram illustrating the basic elements of a tribotronic system is presented in Fig. 2. It contains at least one sensor to measure a loss output, a control system, and feedback to an actuator and a user interface.

A tribotronic device can be visualized as a conventionally passive tribological component or system that has been augmented by some form of actuatable capability, allowing it to actively control its operating state to respond to changes in either its own condition (e.g., changes in dimensions due to wear) or a demand level (e.g., causing changes in lubricating film thickness). The device will include at least one sensor, an actuator, and a control system to allow feedback to achieve an optimal operating state. The concept has been compared to mechatronics. However, several crucial differences exist. In particular, in mechatronics, measurements of "state variables" are involved in the output, and feedback is used to optimize a state variable. In tribotronics, "loss outputs" are measured instead for control purposes. These variables include friction force, temperature, lubricant film thickness, etc. This leads to a need for a greater understanding of the system response, as a complex range of interdependent factors need to be adjusted to maintain control of a specific interface. For a fluid film bearing, these factors include the lubricant flow rate, bearing temperature, fluid film thickness, lubricant viscosity, and power loss. To achieve effective control, these parameters must be "traded off" to obtain specific operating conditions. Interconnections of such nature do not generally exist in mechatronics. Other contrasts with mechatronics are also evident. In addition to having controllable mechanical elements, the physical and chemical properties of fluids, such as viscosity and acid number, are also seen as controllable, and this area offers some of the most exciting opportunities for moderating the properties of sliding and rolling interfaces. Finally, in contrast with mechatronics, some of the scientific principles behind these approaches, which are required to make interfaces controllable, are still not fully established. Consequently, additional scientific understanding must be established through research to permit further engineering developments. This situation includes a very large field of research investigating the controllability of surfaces and interfaces on a molecular scale. Much of this field is related to the study of friction and wear, and it is anticipated that if these developments can be applied effectively on a larger scale, they could have a significant effect on both tribology and the development of future tribotronic devices. Finally, the control system of the system in Fig. 2 also includes ML and a connection to IoT. This allows adaptive learning and control, which can be

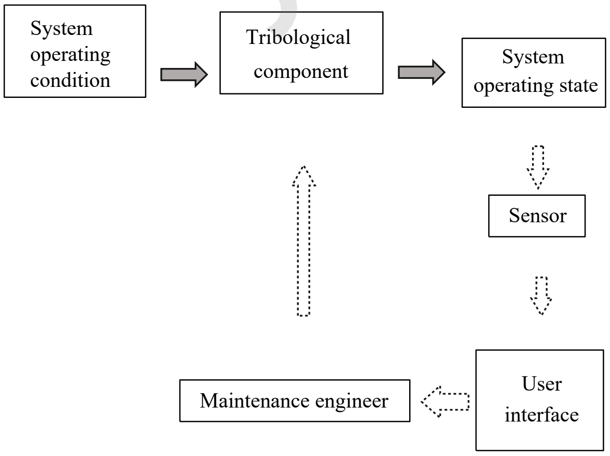

Fig. 1 Schematic of a basic machine element.

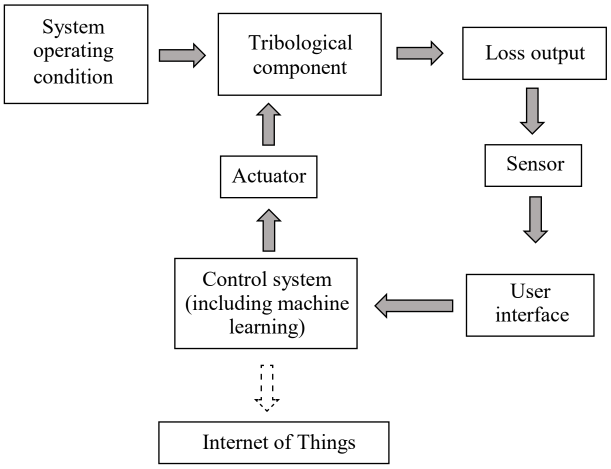

Fig. 2 Schematic of a tribotronic system/CTS.

communicated through connections between groups of machine elements. This aspect illustrates that a tribotronic device can evolve easily into a CTS, which is able to learn and evolve its operation autonomously.

There are at least three main purposes for a tribotronic system.

(1) Tribotronic systems can enhance the functional capability of a device. For example, increasing the load-carrying capacity, reducing power consumption, or controlling excessive vibration in resonant operating states (by instigating a change in interfacial stiffness) can be achieved.

(2) Tribotronic systems can be adopted to offer increased levels of device management and observation, which can be used to increase maintainability, operational availability, and extended lifetime. For example, the response to a change in the geometry of a lip seal due to wear could be automatically compensated for by an increase in contact pressure. The subsequent frictional (power) losses may be greater, but the primary function of leakage prevention may be maintained.

(3) The use of ML can be implemented as a tool in cases where an analytical response to gain optimization cannot be clearly established. In these cases, ML can be continuously developed to gradually perturb the tribosystem on a long-term basis, modifying control responses and learning to optimize performance in specific tasks.

The term "tribotronics" was coined in 2006 and is still not widely used, although many systems are in use and are under development worldwide, meeting the definition of a tribotronic system. The terms "active tribological system" or "hybrid tribological system" are sometimes used for systems that can be viewed as tribotronic, but often, they are simply viewed as mechanical systems with feedback or as a mechatronic system. Section 3 of this paper provides a brief overview of the state of the art for controllable tribological machine elements and surface interface components. This review includes a few specific devices that have the ability to adapt their operating state to optimize their performance under differing prevailing operating conditions. These devices meet the definition of "tribotronic", even though they may not be identified as such when described by their developers. Their complexity and widespread use illustrate that sophisticated control of familiar and well-established (tribotronic) engineering components is both feasible and realistic. Finally, to avoid confusion, some electronic engineers have begun to use the term "tribotronics" in association with the creation of an electrostatic potential through contact or rubbing in devices called triboelectric nanogenerators (TENGs) (see, for example, Ref. [20]). In this paper, the authors refer to mechanical systems with feedback as "tribotronic devices" in line with the original definition of this term.

4 Tribotronic systems: state-of-the-art

A significant number of tribological components and systems currently in use or under development, can be interpreted as tribotronic, and almost all of them, including some devices that are sold commercially on very large scales, are devices that were formerly passive tribological systems.

The control of interfaces and fluids, as well as the control of components and systems, falls within the scope of tribotronics. The section below presents examples of control approaches for both mechanical and fluid systems. The discussion is not intended to be a comprehensive review; rather, it aims to capture the range and capability of the developments that are underway to illustrate progress and inspire an understanding of what potential capabilities may lie in the future.

4.1 Machine elements

4.1.1 *Bearings*

One well-established, actively controlled bearing has been in commercial use for several decades. Electromagnetic bearings are widely used in a range of specialized applications. These include centrifuges (as they can operate at very high speeds and other types of bearings may not be suitable for operation at these speeds) and vacuum systems (as such, bearings can operate without fluids in critical areas, which may otherwise be contaminated by the presence of such lubricants) [21]. The electromagnetic bearings consist of a rotating metal shaft, which is located in a set of electromagnets. The electromagnets are used to induce eddy currents in the shaft as it rotates, generating a magnetic field that has a polarity that opposes that of the electromagnet. A set of proximity sensors is used with feedback electronics to maintain levitation of the shaft, preventing contact with stationary components during rotation. The aim of electromagnetic bearings is to prevent surface contact entirely, and some argue that, as a consequence, they are not tribological devices. However, they clearly demonstrated how bearings can be controlled via feedback to manage friction and wear.

Hydrostatic bearings constitute another form of bearing that is sometimes actively controlled to achieve useful effects. They are discussed as part of an extensive review by Breńkacz et al. [22] and in a specific example described by Ref. [23]. Feedback-controlled versions of these devices have been available commercially for many years. For example, the commercial system described in Ref. [24] uses several high-resolution proximity sensors to monitor the clearance between the shaft and bearing surface and identify the position of the rotating shaft within the bearing in two or three dimensions. The signals from these transducers are used, in association with one or more proportional-integral-derivative (PID) controllers, to control servo valves that selectively deliver pressurized fluid to actively manage the position of the shaft. The arrangement offers advantages in several areas, including the control of whirl instabilities.

Several tribotronic bearings in the form of hybrid bearings of various types have been investigated. These include hydrodynamic bearings, which use different types of actuators, including electrical actuators [25], tilting-pad journal bearings controlled by different nozzle-pivot positions [26], piezoelectric actuated components [27], hybrid bearings employing a combination of hydrostatic and hydrodynamic arrangements to support the load [29], and devices actuated by electromagnetic fields [29]. By adopting these actuated forms, it becomes possible to actively manage the ability of these systems to change operating parameters such as the load carrying capacity, lubricant flow rate, temperature characteristics, and power loss. Additionally, actuation allows other elements to be managed. In particular, bearing dynamics can be actively controlled to avoid resonance.

4.1.2 *Active clutches*

Wet clutches were developed in the 1930s. They are clutch systems that operate with oil lubrication to provide cooling and control friction dynamics. Compared with dry clutches, they have always offered the opportunity to operate more smoothly under changes in torque and generally confer other advantages, such as extended lifetimes. Wet clutches have been used by passenger cars with automatic transmission systems for many years. A change in gear in older passenger cars with automatic transmission is often accompanied by a small "jerk" as one gear disengages and a new gear engages. This jerk arises as a consequence of the torsional dynamics of the drivetrain during torque transients [30]. Gear changes for modern automatic systems are much less obvious. This arises because modern clutch systems are effective tribotronic devices that incorporate electronic control of timing and load changes.

Modern wet clutches integrate pairs of clutches, which can be engaged simultaneously by electrohydraulic valves. In operation, one clutch is used to transfer torque, whereas the other clutch is preselected for a gear change. This permits gear changes to be made in a very short period of time, typically a few tens of milliseconds, minimizing the interruption of torque and facilitating smooth changes. To achieve this, sensors, an electronic control unit, and predictive control strategies have been developed and incorporated to operate these systems [30–32]. In commercial applications, the control units monitor factors such as rotational speed and transmission ratios and use control strategies to enable smooth and efficient gear changes to be automatically implemented as a function of the prevailing load and speed conditions.

4.1.3 *Transmissions and gears*

Fundamentally, transmission systems allow the delivery of torque and speed to be adjusted in rotating systems. There are many types of transmission systems, both manual and automatic. In manual systems, the feedback loop for the choice of gear ratio is formed by a human operator, and they are still extensively used. However, effective automatic transmission systems have emerged over the last century. These systems can be considered tribotronic systems.

Automatic transmissions have been widely used in passenger cars in the form of epicyclic gearboxes with fixed ratios, which have been conventionally adjusted via a clutch system in response to the pressure generated in a fluid-based coupling that links the transmission to the engine. Since the 1980s, automatic transmissions have incorporated increasing sensing and control capabilities, allowing various types of optimization. Detailed models for control have also been developed [33, 34].

Continuously variable transmissions (CVTs) are one particular form of automatic transmission. Several types exist, including belt and chain systems [35], cone-based devices [36], and toroid-based devices [37]. Conventionally, CVTs have been used as low-cost gear systems for devices such as snowmobiles, golf carts, and scooters. However, some recent designs have been relatively sophisticated, as their use in passenger cars has increased to support the downsizing of engines. A review of design and modeling approaches for CVTs is presented in Ref. [38]. Specialized control systems for CVTs to improve device functionality have been developed [39], and “ML” to improve efficiency when in service [40], turning them into cyber tribotronic systems, has also been studied.

Other forms of transmission systems also exist. For example, magnetic (“magnomatic”) gear systems are used to transmit torque between the input and output shafts in systems where direct mechanical contact may not be appropriate. For example, sealing is required in vacuum systems or in marine applications. Magnomatic systems reduce noise and can operate without lubrication in the power transmission zone [41]. Feedback control systems for these devices focus on managing a range of issues, including “pole slipping” and damping [42].

4.1.4 *Active braking systems/traction management*

Maintaining a continuously rolling and essentially nonsliding point of contact is a basic requirement of many wheeled transport vehicles. In dry and clean conditions on flat surfaces, this is generally straightforward to achieve. However, under wet or icy conditions or when gravel or other debris, such as leaves, are present, challenges can arise in maintaining an appropriate level of traction between the rolling vehicle wheels (driven or braking) and the counterface. To help maintain reliable operation in poor conditions, a long-established tribotronic system has been employed. Anti-lock braking systems (ABSs) are widely fitted with road-going vehicles such as passenger cars, trucks, and busses. They are also used on other vehicles, such as aircraft and rail stock.

The basic ABS operates by using a control system and feedback from wheel-based sensors to maintain wheel rotation during braking, preventing “locking-up”. Many of these systems operate fundamentally by controlling the pressure in individual brakes in response to feedback from sensors, which detect when one or more wheels move more slowly than the vehicle speed. Control systems may use a simple on–off approach or more complex PID-type systems [43]. More sophisticated systems also control additional features, including changing the balance of the brake load between different wheels or applying the brakes selectively to control the vehicle direction if the control unit detects a difference between the steering angle and the vehicle direction. These systems are called “cornering brake control (CBC)” systems. All of these control systems adjust the levels of grip to allow better control of steering and vehicle stability. Recent research has considered the application of ML for ABSs [44].

The ABS can also be used to control vehicle traction under acceleration. Traction control systems (TCSs) are able to use ABS components with additional control software and throttle control systems to ensure that the wheels do not slip when rotating under acceleration.

ABS is a mature and widely used technology with many variants, and it can be designed and manufactured at economic rates. However, evidence suggests that friction between tires and road surfaces is a nonlinear function of wheel slip requiring special carefully designed control algorithms [45], so the issues of vehicle control systems to manage braking are still the subject of further development and research. This issue is currently an important consideration, as battery-powered passenger cars are typically 20% heavier than cars with an internal combustion (IC) engine. An increasing number of these types of cars are being fitted with autonomous driver systems, and such vehicles are expected to operate safely in a wide range of weather conditions, including rain, ice, and snow, so sophisticated control of braking systems is needed.

4.2 Fluids and lubricants in tribotronics

A wide range of fluids are used in tribology, most commonly lubricants, which provide cooling and reduce friction and wear. Lubricants are mainly used to form a thin barrier/shear interface between sliding or rolling interface components. These fluids may be gases or liquids, and their regime of operation is commonly classified according to the type of load-carrying film that they create. The commonly recognized lubrication regimes are boundary lubrication, mixed lubrication, hydrodynamic lubrication, and elastohydrodynamic lubrication (with four subcategories: elastic iso-viscous, rigid iso-viscous, elastic piezo-viscous, and rigid piezo-viscous contact). Liquid lubricants are often complex formulations involving a range of additives to optimize different aspects of their operation, such as their temperature–viscosity behavior or wear protection characteristics. These additives themselves may also be liquids. Lubricants and liquids, in general, are critical elements of any tribological contact, and their dynamic control, by methods other than adjusting viscosity by changing the temperature, has only relatively recently been considered.

4.2.1 Lubrication of metal cutting systems

The use of temperature control and lubrication in single-point and multipoint cutting in machining operations is common in the manufacturing industry. However, these approaches are often implemented suboptimally, without feedback, which opens the possibility of adopting closed loop control to manage them more effectively. Busch et al. [46] investigated potential cooling strategies involving high-pressure cooling, cryogenic cooling, and aerosol dry lubrication to reduce energy consumption and improve product quality. Studies of this type, which develop fundamental relationships between machining conditions, tribological parameters, and quality, introduce the possibility of implementing feedback control for processes of this type.

4.2.2 Relubrication systems

Online relubrication systems for machine elements are also a well-established approach to maintaining lubricant levels, and basic guidelines are available for managing these processes. In the past, relubrication has been either a continuous process or an interval-based process, often controlled via an automatic timer with relubrication volumes on the basis of operating conditions [47]. More recently, on-line relubrication intervals have begun to move toward condition-based management strategies. Commercially available approaches involve monitoring both low-frequency bearing vibration levels [48] and ultrasonication [49] to provide a control signal for automatic relubrication. Relubrication is initiated if the set signal levels are exceeded. This technique can be optimized via appropriate signal processing [50].

Automatic relubrication is commonly used where extra lubricant is needed relatively frequently, especially if there are many such locations with a relubrication requirement in a machine or plant, and automatic lubrication is particularly valuable in situations where manual access for relubrication is either very difficult or impossible.

The management of mechanisms used in space is one extreme circumstance where manual or automatic relubrication can be valuable. Manual relubrication in space is difficult, so it is rarely used. However, in one example [51], fluid film relubrication was used to manage cage instability in the support bearing for a reaction wheel in an ESA space observatory for X-ray astronomy. Unstable monitoring of the observatory was used to diagnose a rolling element bearing cage fault, and manual relubrication was used to effectively resolve the issue. Bearing lubrication is an important issue in space vehicle design, as limitations in the lifetime of lubricants can, if not carefully managed, impose a limit on mission duration.

The automation of existing manual systems for fluid film lubricants seems to be an entirely plausible step, and prototype systems for solid lubricant replenishment have also been described [52, 53]. In this system, a solid lubricant is applied by a micro heater, which is activated when friction exceeds a set limit. The evaporation of indium onto the bearing results in lower friction, allowing the component lifetime to be extended considerably in comparison to “once only” lubricated components for space mechanisms.

Importantly, liquids, gases, and vapors can all also be used as lubricants and may play a role in tribotronic systems. In particular, water vapor may play a valuable untapped role in moderating friction. The presence of water vapor is well known to influence the lubricating properties and low wear characteristics of graphite-based solid lubricants. However, the friction properties of many other materials, including diamond-like carbon (DLC), ceramics, silicon, and metals, as well as solid lubricants such as molybdenum disulfide and boron nitride, are also influenced by the level of water vapor present [54]. This phenomenon opens up the possibility of using humidity levels to control friction in a range of tribotronic devices. Gas lubrication is already in use in high-speed aerodynamic bearing systems. However, it could also be used as a moderator of friction coefficients in dry contact. The friction of carbon nitride coatings can be controlled by gas lubrication [55, 56]. Dramatic changes in the friction coefficient between 0.01 and 0.2 were obtained for a carbon nitride/silicon carbide contact by changing the rate of flow and delivery angle of nitrogen gas flow. This technology may have value in tribotronic control of friction in a range of applications, including MEMS components.

4.2.3 Control of rheology

The rheology of some fluids can be altered by means of electric or magnetic fields via various approaches. Fluids, called magnetorheological fluids (MRFs), are composed of a base fluid, microscale ferromagnetic particles, and additives such as surfactants to minimize particle sedimentation [57]. A wide range of liquids, from oil to water, can be used in the formulation of MRFs. MRFs are widely used in special machining processes requiring control of the machining agent, such as magnetorheological polishing [58]. The fast and reversible changes in the rheology of MRFs also make them useful in a variety of applications, such as adaptive suspension systems, dampers, and haptic devices [59]. The response is greater if larger particles are used, but particles larger than 100 microns may be problematic when used in mechanisms, as they may cause high friction, jamming, and wear. Ferrofluids are similar to MRFs but are formed from colloidal suspensions of magnetic nanoparticles. They provide much better stability against sedimentation, but their rheological response tends to be weaker than that of MRFs. Ferrofluids have been investigated for use in sealing technology [60].

In machine components, the characteristic dimensions of the tribological contacts are often small, making focusing magnetic fields extremely difficult. However, focusing is not a limitation for electric fields that can be created in nanometer-thin elastohydrodynamic films by changing the electric potentials of lubricated surfaces. Different methods exist to make fluids respond to electric fields. A common approach is to suspend solid particles in an insulating liquid, such as mineral or silicon oil, using functional additives such as surfactants. The particles, typically made of ceramics or polymers, are polarized in the electric field, producing a rapid change in oil viscosity. The change is reversible and controllable. Electrorheological fluids (ERFs) have already been applied in aerospace and robotics and have been integrated into mechanical systems such as clutches, shock absorbers, dampers, and valves [61].

The solid particles used in the ERFs and MRFs are not ideal for tribological contacts, as they cause wear and increase friction. Another solution is to use liquid crystals. Liquid crystals have already been tested in various tribological scenarios [62, 63]. The advantages and limitations of these methods are described in Ref. [64].

4.2.4 Control of friction and film thickness

Various approaches to control friction with electric and magnetic fields are considered in Ref. [65]. A recently developed approach to formulate tribotronic fluids that overcomes the shortcomings of multicomponent MRFs and ERFs in lubrication is to use ionic liquids (ILs). ILs are generally defined as salts with melting points below 100 °C. Some ionic liquids have been known for more than 100 years, but interest in their use as electrolytes has increased significantly over the last thirty years, and their potential in tribology is becoming evident. ILs have a unique property set, which is unavailable from "conventional" or "nonionic" molecular compounds, rendering ionic liquids exceptional materials for tribotronics and bringing them under more intense scrutiny.

ILs can be designed to have low volatility, a virtually non-existent flash-point, the absence of hazardous vapours, high thermal stability, and large liquid ranges as a function of temperature. These factors have proven to be important drivers for research in many industrial applications, some of which are within the energy area. This intensified interest has led to an explosion in the number of new cation classes, stretching from the well-recognized azolium (such as imidazolium and triazolium) to phosphonium, ammonium, pyridinium, and pyrrolidinium.

Anions include a wide variety of inorganic ions (e.g., halide, nitrate, perchlorate, sulfate, nitrite, hexafluorophosphate, tetrafluoroborate, and azide), but more recently, an ever-increasing number of organic species (e.g., triflate, benzoate, sulfacetamide, alkyl-sulphates, alkylcarbonates, carboxylates, phosphates, and orthoborates) have also been adopted.

Attempts have been made to control the rheology of ionic liquids by applying a voltage across the gap between plates in a rheometer [66]. The data acquired from these experiments revealed a change in friction. This was originally attributed to changes in the ionic liquid, but closer analysis of the results later revealed that the change in torque came from surface changes in the electrode–shaft contact. A thin layer of copper was deposited on the steel shaft, causing a change in friction [67].

Ionic liquids can also be made magnetic by incorporating complex ions of metals that have a high magnetic moment. An example of such a fluid is $[C_4C_1Im][FeCl_4]$ [68]. These fluids can be used in the same way as ferrofluids, but the intrinsic instability through the precipitation of particles is completely absent. The response of the IL to magnetic fields can be enhanced by using rare earth cations [69]. The magnetic ILs reported thus far are predominantly based on halogen-containing ions and are thus currently not suitable for lubrication applications.

Since ionic liquids are composed of molecules with a net charge, they are expected to be more surface-active, supporting the formation of protective boundary layers. It has been shown that ionic liquids form structurally different interfacial layers depending on the surface charge [70–72]. The ionic layer structures and responses to electric fields have been studied via a wide range of techniques, including quartz crystal microbalance (QCM) [73–75], atomic force microscopy (AFM) [76–78], vibrational sum frequency spectroscopy (VSFS) [79], and neutron reflectometry (NR) [80–82]. The experimental results are generally in agreement with those of molecular dynamic simulations [83], but large cations and anions are still challenging to model because a limited number of atoms can be included in the calculations [84]. Another issue is that most of the research is still done using halogenated ILs, with fluorinated anions being the most common.

In general, for lubrication applications, halogen-containing ions are undesirable because they promote the formation of corrosive and toxic species, resulting in wear processes for metallic surfaces [85]. Therefore, there is now significant interest in nonhalogenated ILs. Instead of halogens, other tribologically active elements, such as boron, nitrogen, and phosphorous, are incorporated into the cationic and anionic parts of ILs. These cations and anions may then interact "synergistically" with the lubricated surfaces. A popular class of ionic compounds with exceptional anti-wear and friction-reducing properties is chelated orthoborate-based ILs [86–88].

With respect to lubrication, ILs offer a wide range of advantages over traditional lubricants, as they can be designed to withstand high thermal and pressure stresses and to specifically react and decompose at certain temperatures and pressures, such as in lubricated contacts in machines. In addition to charge interactions, ILs can also be endowed with various surface interaction mechanisms.

A recent advance involves the use of ILs in oils to control the boundary lubricating films and, thus, the friction response [89]. To achieve better solubility in nonpolar oils such as polyalfaolefins (PAOs), anions are alkylated [90, 91]. However, this may result in low surface activity for such ILs [92].

A recommended way to study the solubility of ILs in oils is to use nuclear magnetic resonance spectroscopy. This provides crucial insight into the chemical conditions of the blend. This also indicates whether the ions are dissociated. Dissociated ions are key in providing surface activity and ionic conductivity. It was shown in Ref. [93] that the degree of dissociation of different ILs in base oil influences their tribological performance. The degree of ion dissociation was estimated by measuring the ionic conductivity of the oil–IL blends. Clear differences in the degree of dissociation between the orthoborate and phosphate blends were observed. The ion dissociation in the orthoborate IL blend was at least two orders of magnitude greater than that in the phosphate IL blend. A low degree of dissociation of the phosphate anions points toward a smaller separation between the cation and anion charge centers, implying greater electrostatic attraction between the ions. The ion pairs formed by the phosphate IL in the base oil are likely to be surrounded by a nonpolar hydrocarbon region formed by the hydrocarbon chains attached to the charge centers (Fig. 3(a)). Delocalized charge centers of the orthoborate anions are likely to result in greater charge separation from the phosphonium cation and, therefore, a greater degree of dissociation (Fig. 3(b)). Dissociated ions are driven to the lubricated surface rather than remaining in the lower polarity base oil.

A hierarchical, layered structure (Fig. 3(c)) is formed by the orthoborate anions and phosphonium cations. This structuring provides lower friction and better wear protection than neat base oil. The phosphate anions have been decorated with long alkyl chains to provide high solubility in base oils; hence, these anions are more likely to remain in bulk. Even if driven to the surface, the phosphate IL will exhibit weaker adsorption at the surface, forming a mixed interfacial layer rather than a layered structure (Fig. 3(d)). These ionic boundary films are not lubricious and provide poor surface protection.

Knowledge of the degree of ion dissociation is vital in formulating electrically conductive lubricants [94] and, more importantly, when designing tribotronic systems.

Tribotronic control of elastohydrodynamic films has been demonstrated [95]. A steel ball in an EHD2 test rig was used as the working electrode, whereas two steel blocks positioned on either side of the ball served as the counter electrode. Experiments were carried out under pure rolling conditions at a constant entrainment speed and load. Figure 4 shows how the central film thickness responded to the applied potential. The first two potential changes (±0.5 V) were within the electrochemical window of the system. Applying larger potentials outside the electrochemical window further increased the film thickness response, especially for the positive potential, leading to a very thick lubricating film. The response was almost instantaneous.

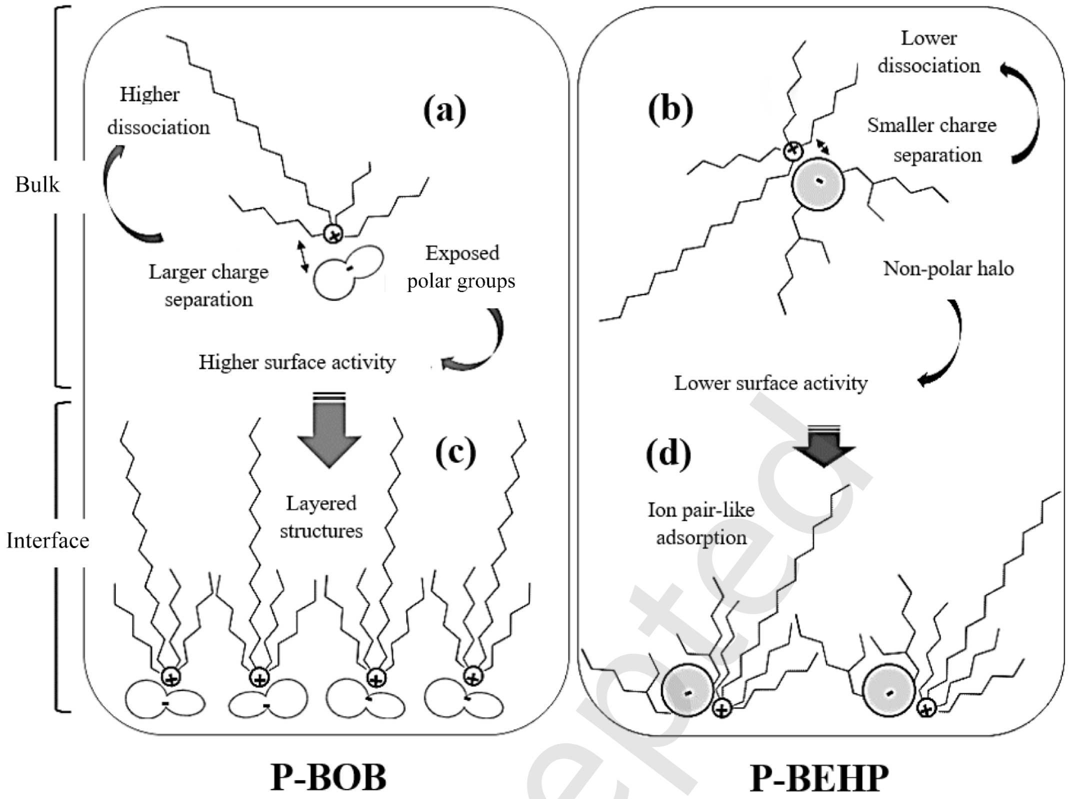

Fig. 3 Bulk characteristics of (a) orthoborate ILs, (b) phosphate ionic liquids, (c) surface adsorption mechanism for orthoborate ILs, and (d) surface adsorption mechanism for phosphate ILs. Reproduced with permission from Ref. [93].

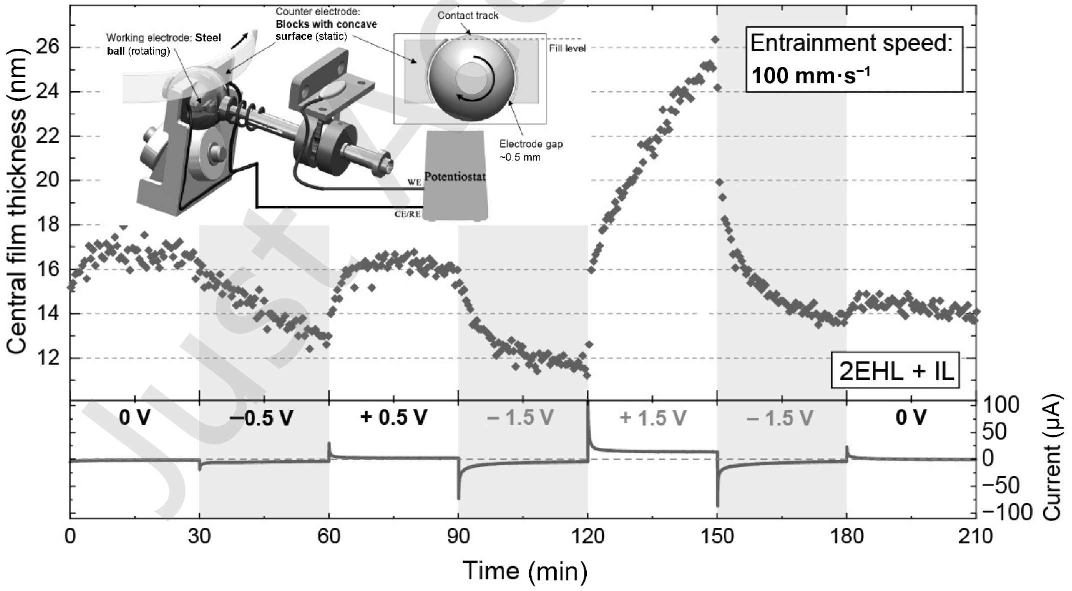

Fig. 4 Central film thickness in an EHD contact for an ester oil with 5 wt% IL. Film thickness responds to a change in the surface potential. Reproduced with permission from Ref. [95].

The subsequent application of the negative potential decreased the film thickness to the initial level.

At high potentials, outside the electrochemical window, the occurrence of oxidation reactions and the resulting accumulation of oxidation products could not be ruled out, but reversibility of the response suggested that any reaction products made only a minor contribution to the overall increase in film thickness. Generally, the response does not need to be reversed, as the film thickness can be increased when it is needed, for example, when deterioration of lubrication is detected. A short burst of high electric potential results in a thick, surface-protecting multilayer ionic film. This ionic technology has the potential to benefit machine components, especially in remote, inaccessible installations such as those in space or offshore.

4.3 Novel devices and machines

The development of active control for tribological components has led to devices that have novel designs and attributes. Like some other actively controlled tribological components considered in this paper, they are not often identified as "tribotronic".

Nevertheless, they represent part of the evolution of the subject. As few representative examples of these more novel systems are outlined in this section.

Fluid film bearings are conventionally only used to support loads. However, bearings in the form of specialized flat air bearings have also been used to manipulate objects via selective pneumatic control of directed air orifices. These arrangements have been used to translate and rotate lightweight components [96]. For example, the control of both normal and lateral air flow in bearing systems has been used for precision manipulation of thin-film wafers [97]. Such developments demonstrate how introducing control into formerly passive systems can be adopted to create new forms of components that have capabilities hitherto not considered.

Another example of a novel system involves the use of ferrofluids as a means to control the flow of other fluids (lubricants), such as air inside a lubricated interface. In this context, ferrofluids have been investigated as controllable barriers (effectively using them as partial or complete fluid seals, which can be adjusted via electromagnetic fields) at various positions at the interfaces of otherwise conventional bearings to control the flow of lubricant within the bearing clearance. In this location, as media sharing the interface, these fluids have been used to manipulate the capabilities of bearings by restricting lubricant flow in specific locations in the bearing via external fields. Investigations to study stiffness [98], friction [99], and load capacity [100] have been conducted. Ferrofluids have also been implemented as actuated bearings in long-stroke aerostatic actuators for precise positioning [101].

Lip seals are conventionally passive devices designed to operate with a fixed limit of sealing capability under specific conditions of sliding and differential pressure. Tribotronic lip seals have been developed, which contain actuators to adjust the contact pressure between the shaft and seal lip to control the balance between the contact pressure (which controls power loss) and leakage rate [102]. The notable advantage of this arrangement is that the lip contact pressure can be adjusted to the minimum value, which just maintains sealing, thus minimizing power loss while still keeping leakage to a minimum, even under conditions when the component dimensions may vary. For example, wear during operation may be caused by asymmetry due to misalignment, or dimensional change may be caused by variations in ambient temperature.

Approaches to managing the lubrication of IC engine cylinders have also been developed via tribotronic systems. The form of the process of lubrication varies slightly according to the type of engine under consideration. Conventional IC engines for most road transport applications, such as passenger cars, trucks, and buses, rely on the passive action of a set of sealing rings on the piston to manage the splashing or spraying of lubricant directed onto the engine cylinder underneath the piston-skirt. However, in some larger engines, for example, large two-stroke marine diesel engines, there is a different arrangement where the lubricant is injected into the engine cylinder above the piston. In this latter case, the lubricant performs two functions: It lubricates the piston, and it serves as an agent to supply an alkyne additive to the cylinder to counteract the corrosive effect of acid combustion products. Generally, the lubricant supply rate is governed by the anti-corrosion requirements. More lubricant is supplied at higher loads and speeds to maintain the balance between the corrosion-neutralizing additive and the amount of sulphur in the fuel. This results in overlubrication (with additional oil being mainly combusted with the fuel) but maintains corrosion control. An active lubrication supply system has been proposed that separates the lubrication and corrosion control requirements [103]. Lubricants and neutralizing additives are supplied separately according to their individual demands. The system has significant potential value for reducing emissions and lubricant consumption for large marine engines [103]. This has also led to an approach for measuring lubricant flow in engine cylinders [104]. It also offers the possibility of reducing the friction of piston-ring packs in roadgoing vehicles.

5 Challenges and opportunities in the development of tribotronic systems

To be tribotronic, machine elements require three additional principal elements. These are an actuator, sensor(s), and a control system. In the context of tribotronics, each of these elements is at different stages of maturity. Classical control methodologies, such as PID systems, are well understood and widely implemented in other engineering applications and could be used in some tribotronics systems. Sensors for some variables, such as temperature and fluid flow, are also well-established as devices that are useful in tribology. However, it is notable that the sensing of "loss outputs", such as friction, power loss, and lubricating film thickness, is less straightforward, and some development of the indirect methods used to date would be valuable in this context. Finally, actuation is probably the least developed component in tribotronics. The challenge here is usually to determine a suitable method for actuating a component that is conventionally passive, and the approaches to this are not often particularly obvious. The sections below present discussions on each of these system elements.

5.1 Challenge of actuation

The field of tribotronics is growing, and as the steps that will lead to the successful development of commercial active systems become clearer, it seems probable that applications where condition monitoring is already widely used offer one of the most likely first opportunities for the implementation of tribotronic systems. The key challenge appears to be "what kind of actuation can be implemented to respond to a sensor signal?" This arises because many conventional tribological components are structures that have either been designed so that they cannot be adjusted and always operate in the same way or that dynamically respond in a specific identical way to changes in operating conditions. For example, a lip seal basically operates with a fixed nominal contact pressure against the counterface (although this pressure is moderated slightly by changes in the differential pressure it seals against), and tilting pad bearings can dynamically adjust their operating state in response to changes in, say, speed or load. In these cases, the device response cannot be changed after installation, and the devices are incapable of meeting new alternative optimization goals.

Given the uniqueness of the challenge of developing actuation for passive devices, one generalized approach that could be valuable in addressing this challenge is to adopt the semistructured design methodology TRIZ [10]. TRIZ is specifically suited to such challenges where solutions are not obvious. TRIZ also presents a range of redesigned options and can be applied in a way that narrows the range of possible solutions. The method has already been applied in tribology to study redesign for the actuation of tilting sliding pad bearings [105].

5.1.1 *Actuation of mechanisms*

One group of tribological components is formed by systems that have passive adjustments. In many of these cases, an equilibrium is often formed between two forces. The latter category includes devices that operate on hydrodynamic principles, such as journal bearings, tilting pad bearings, and some seals. In these cases, the load to be carried is balanced by a force generated by hydrodynamic action during proper operation of the component. Devices of this type are more straightforward to control because the passive functional change can be replaced by an actuated functional change. As a result, one class of tribotronic devices that have been developed to date is of this form. For example, actuated hydrodynamic tilting pads have been used [26–29].

Devices that do not already include physical passive adjustment form a greater challenge from the perspective of actuation, as the form of the actuator required is not immediately obvious. Rolling element bearings constitute a large proportion of bearings used in commercial applications, and commercial organizations see them as components that can benefit from condition monitoring. A few commercially available devices now have integrated sensor systems, data acquisition capabilities, and communication capabilities.

Separate encoder systems for bearings that provide information about speed, number of rotations, etc., have been available for many years. However, over approximately the past decade, several small and relatively low-cost commercial tribological bearings with built-in sensing capabilities have arrived on the market. One large European-based rolling element bearing company has introduced a wireless rolling element bearing product that has integrated technology to measure and communicate its operating state [106]. The system uses internally powered sensors and a data acquisition arrangement to collect information about a number of operating details, including the rotating speed, operating temperature, vibration levels, and bearing load. Wireless communication is used to send information to a central location for condition analysis. In a similar step, a German polymer-bearing manufacturer now markets a system for wear sensing that can be implemented on a wide range of their polymer bearings [107]. Essentially, it operates by including at least one conductive film layer as part of the construction layers of the bearing. When the conductive film is broken, the changes in resistance indicate that linear wear has reached a defined point within the bearing wall thickness. However, neither of these bearing types have an actuator with only sensing elements.

Although sensing is developing, methods to actuate rolling element bearings are not obvious. However, one approach to actuation for rolling element bearings has been taken for cases where bearings are loaded radially and unidirectionally, for example, to support the weight of a horizontal rotating shaft. In this instance, the radial load concentrates the raceway wear in a limited (load bearing) area of the lower part of the outer raceway. A novel system that rotates the race of standard bearings over time to spread loads across the entire raceway has been developed [108]. Trails of this bearing design suggest that the approach can significantly extend its operating lifetime by up to 500% [109]. Although the cost of such a bearing is high, it offers significant potential advantages for applications where bearing replacement would be costly and/or inconvenient, for example, for uses involving wind turbines operating at sea or in other remote and inaccessible areas.

5.1.2 Actuation of lubrication

A second way to manage the operation of rolling element bearings is to manage the lubricant supply. In cases where there is a continuous flow of lubricant through these bearings, the lubricant flow rate is conventionally determined by the requirements of temperature management, and steady flow rates are often determined on the basis of the maximum cooling requirements expected. However, high flow rates are not always needed for cooling, and other priorities may prevail in governing the delivery of lubricant. The effects of single-drop lubrication on lubricating conditions [110] and the potential use of “drop-on-demand” methods [111] have been investigated as methods of supplying oil for elastohydrodynamic contacts with the aim of achieving an optimal (minimum) supply. The on-demand delivery of lubricants for rolling element bearings used in space has also been considered. These systems monitor a range of variables, including the bearing temperature, friction torque, and motor drive current, to determine demand, delivering lubricant in predetermined volumes from a stepper motor-operated system [112]. These approaches may be valuable in a range of applications, but they are particularly valuable where relubrication would be useful to extend the life of inaccessible mechanisms and where only very low levels of lubricant supply are needed.

Lubricants are frequently complex formulations of a range of constituents, including mineral oils and additives, in lubricant packages to control critical elements of their physical and chemical capabilities. Additives generally become depleted during lubricant use, causing a deterioration in lubricant performance. Conventionally, lubricant conditions are monitored through regular sampling, laboratory analysis, and written reports (which are now generally communicated to clients via the web). On-line evaluations of lubricant conditions are being developed, and the range of sensors used to monitor different aspects of lubricant and additive conditions is increasing [113]. Investigations to consider how lubricant packages can be directly monitored and maintained during operational use are extremely rare in the literature. However, some commercial systems adopt indirect approaches to improve additive content on the basis of their operational duties. For example, one system for IC engine lubrication removes a proportion of the used oil from the sump on the basis of engine duty data and replaces it with fresh oil to improve the additive package mix [114].

To monitor the additive content effectively, sensors that can monitor chemical properties are needed. Bench-based equipment has been used in the past to monitor additive concentrations. For example, Fourier transform infrared technology was used to control the level of an antioxidation additive in rapeseed oil in a thermal and oxidative test in a laboratory system [115]. On the whole, systems operating in the field do not justify the implementation of such expensive analysis systems on a dedicated basis. However, the equipment required for chemical signature analysis is rapidly reducing in price and becoming more compact, so it is likely that real-time monitoring of additive content in lubricants becomes a cost-effective possibility. Once this process becomes reliable, actuation by the simple step of real-time additive mixing becomes a feasible “next step”.

5.2 Challenges of sensing

In general, the sensing of safety-critical systems and high-value assets, facilitated by reliable sensors operating with various forms of connectivity, such as Bluetooth, has been increasing for many years. The availability of reliable, increasingly miniaturized sensors and electronic modules for communication has supported this trend. There are a number of clear advantages gained by including sensing in components. For example:

- Sensing the condition and recording the history of the duty of a device makes it possible to assess the potential remaining life of machine elements more precisely to manage maintenance schedules and prevent unplanned downtime (breakdown).
- Sensing can be used by both component suppliers and users

to collect data regarding patterns of operation, use, and failure. For example, to ensure that devices are always operated within their design capacity.

- The integration of sensing systems also has significant potential for applications within industries where operation is remote, such as offshore wind turbines, or where safety may be a critical factor, such as aircraft engines. It can also be employed in the parts of static machines where access is inconvenient, or it is undesirable to stop the operation of machines for inspection of wear.

Given these advantages and other factors, such as falling costs and rising demands to operate engineering systems in a sustainable fashion, the trend toward integrating sensing into machine elements is likely to continue. This development is supported in the area of tribology by several other factors:

- A wide range of sensors to detect the condition of the interface surface are under development [116], which will support the monitoring of tribological conditions.
- The possibility of incorporating self-contained power sources, including TENGs and other miniature power sources, in conjunction with small rechargeable batteries to support the operation of sensors and communication systems is now a reality, as is the autonomous monitoring of mechanisms in machines.
- The increasing use of sensors and monitoring systems in machines facilitates the implementation of tribotronics, which can incorporate both conventional control and ML.

It is clear that some "loss outputs" are difficult to measure directly, and in some cases, a bespoke arrangement is required that is linked to a specific type of device. For example, the measurement of friction frequently requires a customized arrangement, and the design of an oil film thickness sensor may be linked to the scale of the film thickness to be measured. In these cases, the use of a "proxy" measurement may be an alternative, but the selection of proxies should be performed with care, as there may be drawbacks. For example, thermal measurement is sometimes used as a proxy to identify high friction and/or low film thickness. When lubricating films are so thin that contact develops, temperature measurement can be used as a general tool to identify bearing faults by locating hot spots that arise during inadvertent frictional contact. The method only identifies a fault after a period of operation, so significant damage can develop, which requires repair, leading to the potential need for bearing replacement. Therefore, using a proxy that does not rely on detecting a failure condition is generally preferable.

5.3 Challenges of control

Many dynamic engineering systems have control arrangements to drive their condition toward a desired state. These control systems generally aim to achieve the desired output state by measuring the prevailing state at the output and using a feedback loop to adjust the input to drive the output as close as possible to the desired state. The model used to determine the adjustment to an input can be quite simple or very complex, and there is a wide range of well-established modeling methods for this purpose [116].

Many tribological components have a relatively slow response in fully stabilizing to changes in input. For example, a change in load for a hydrodynamic bearing causes an instantaneous change in film thickness, but establishing thermal equilibrium takes at least several minutes because of the thermal capacity of the bearing components and the lubricant volume. Similarly, viscoelastic components such as lip-seals take several minutes to adapt (change shape) owing to new operating conditions as time is needed, generally on the scale of minutes, for polymers to elastically respond to changes in load.

To gain some understanding of the control systems required for a given tribological system, it is necessary to gain insight into the responses of individual components. Step tests, ramps, and sine wave changes in input can be used to characterize the responses of components in a routine fashion, and such tests will be needed to provide valuable information about the responses of individual tribotronic components and the control arrangements needed.

At present, novel control methodologies are not needed for tribotronic components; indeed, their generally simple design and slow response suggests that relatively simple deterministic arrangements, such as PID controllers, which are well established in industry, are likely good first candidates for applications involving the management of individual tribotronic components. However, the embedded computing capability and connectivity of many components or machines allow the use of machine learning ML in a range of contexts, including the control of an individual device as well as collections of devices. As discussed above, ML is already used for predictive maintenance. By collecting data on the duty and wear conditions of many similar components, fault signatures can be obtained to predict the remaining useful life and corrective maintenance processes. As time progresses, these systems will be increasingly effective in assessing the value of improved routine maintenance schedules, gauging the impact of using improved parts in machines, evaluating energy efficiency improvements, etc. In some cases, it may also be possible to determine if new parts have been fitted correctly. In this way, machine components with sensors (and control), data collection, and communication will become an increasingly integral part of Industry 4.0, and ML will support the development of Society 5.0 concepts, supporting increasingly efficient mass production and service processes.

6 Potential of tribotronics

6.1 Future evolution

The development of cyber-physical systems is, in general, seen as inevitable. These developments may not directly impact all mechanical systems immediately, but the value of incorporating additional intelligence, connectivity, and functionality into machines, particularly high-value assets or safety-critical systems, seems too strong to ignore. Moving from one industrial generation to the next always presents challenges and objectors, but as one once observed, "the stone-age did not end because we ran out of stones". The benefits of new technologies in terms of flexibility and convenience eventually outweigh the objections and engineering challenges faced. Therefore, just as the discovery of bronze offered more flexible and elegant designs for tools and other everyday items than those made from stone, the development of components with control, connectivity, and intelligence, whether hardware or software, will inevitably lead to the age of cyber technology. When this technology can convey overwhelming advantages over purely mechanical systems, the cyber-tribotronic subset of components that accompany that development will also evolve.

6.2 Advantages

Tribotronics and cyber-tribological systems offer many potential benefits, as summarized in Fig. 5.

The benefits of tribotronics and cyber-tribological systems include the obvious benefits of controlling friction and wear, with

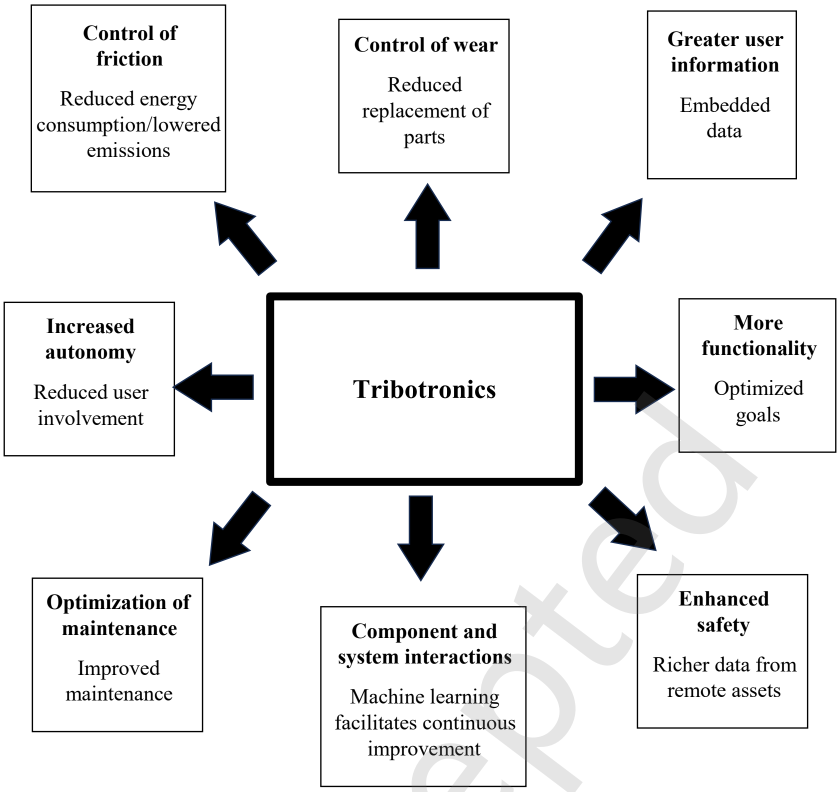

Fig. 5 A summary of benefits of tribotronics and cyber-tribological systems.

the chance of dramatically reducing energy consumption, associated emissions, and waste of parts that will have a prolonged life. However, there are many other potential advantages:

- A greater level of user information—For example, a part may have embedded information about its manufacturing details, installation, maintenance record, etc. It will also be able to record details of its lifetime duty. All these details should lead to improved maintenance practices/schedules and a more managed service life, supporting greater reliability and better prediction of remaining useful life, etc.
- More functionality—Increased functionality will include the opportunity to control power loss, wear rate management, and increased vibrational stability through actively actuated capability.
- Increased autonomy—Machine components can potentially have software-managed performance. This would allow either autonomous control or remote management by human operators. Actuated capability/performance will be “software updateable”.
- Component/system interaction—It will be possible to monitor the performance and issues of sets of components both using human operators and using ML.
- Optimization of operation and maintenance schedules—Enhanced maintenance and greater availability of systems will be achievable through continuous improvement facilitated by communicated learning of whole groups of devices.
- Sensing of safety critical systems and high value assets—Reliable sensors with various forms of connectivity will facilitate higher levels of safety. Bluetooth has been used for many years. The availability of reliable, increasingly miniaturized communications systems is further supporting this trend, and new hardware/software will support further increases in speed and range.

6.3 Production

The mass production of machine elements with sensors will aid the development of tribotronics, and this step is likely to precede the widespread use of machine elements that also have actuators.

The rapid development of AM may play a significant role in the development of tribotronics. AM supports the simple production of complex meso-structures that can have integrated elements, materials, and sensors, supporting the production of devices that were previously extremely difficult to manufacture via traditional methods. As discussed above, prototype systems of novel machine elements already exist, and it seems at least possible that new machine elements may emerge as a consequence of the intricate manufacturing capabilities that AM offers. At the very least, AM offers the chance to optimize internal structures and minimize the weight of tribotronic components as they emerge.

6.4 Standards and priorities

In addition to mass production, the adoption of a uniform approach to the design and operation of tribotronic devices will aid their development. The uniformity of intercommunication, control, and data collection always aids the proliferation of technology. To this end, the production of appropriate national and international standard documents should be considered a priority to smooth the progression and development of the technologies that support tribotronics. This step enables a normalized approach to all stages of technology development across design, testing, calibration, operation, disposal, etc., and ensures the interchangeability of parts produced by different manufacturers.

6.5 Disruptive technologies

Tribotronics itself is only a developing technology in many senses. However, there are a range of new technological themes that may also impact this development in their own right. They include a range of smart materials that respond to heat and light (and may form the basis of new sensors), ionic liquids that may support a new class of widely used lubricants (especially in electrical systems), TENGs (which may support the production of power for sensors), and new forms of communication protocols that may aid machine element communication.

7 Conclusions

Good practice in tribology, as an engineering science, has contributed to the development of more reliable and more efficient machines for more than two centuries, even though the name for this science was coined just over 50 years ago. Developments in many areas, including chemistry, engineering design, physics, mathematical modeling, and simulation, have contributed to extensions in knowledge and improvements, leading to reduced friction (greater efficiency) and lower wear (longer life) in machine elements. These improvements have, in turn, supported the recognition of tribology as a discipline that contributes to reducing the cost of machine maintenance, lowering the cost of energy consumption, and helping support sustainable engineering practices by reducing waste, harmful emissions, and the disposal of solids and fluids.

However, it is becoming apparent that there may be limits to what can be achieved in the future through improvements in the microstructure of materials for machine elements, developments in lubricants and additives, and the evolution of functional coatings. Therefore, these authors suggest that the next "revolution" in tribology could be supported by the development of the same technologies that support the development of society in general. The advent of miniaturized sensors, embedded computing systems, actuator technology, and wireless communications offers the opportunity for the development of active (tribotronic) machine components that can have many positive attributes. In particular, tribological components will no longer be constrained to have a fixed optimization goal. Once they are designed and in service, their performance characteristics can be changed directly by adjustments in their control software. This arrangement affords many benefits, including autonomous adjustment, a record of lifetime duty, the opportunity to optimize different aspects of operation at different times, the chance to incorporate "communicated learning", integration into Industry 4.0 networks, individual self-adjustment (for example, to manage wear), etc.

As the benefits of tribotronic components are potentially transformative for some applications, their development and implementation will likely increase. Potential applications appear to be most likely where some form of sensing/condition monitoring is already applied. That is, where there is a critical asset/safety risk, a clear requirement to plan machine-down time, instances where the performance of critical assets is not known, and where fault propagation may lead to high "costs" (financially or environmentally). Importantly, the systems where tribotronic devices may be applied may not need to have high value in their own right; it is the context in which a machine is used that matters the most.

The evolution of tribotronics as mainstream industrial activity will likely require its use in applications that are conducive to routine implementation and mass production. There are clearly technical challenges to be addressed in the development of tribotronic systems. However, there are other practical challenges. They include the increased initial cost of a more complex electromechanical system, acquisitions of the additional skills required for correct maintenance, greater challenges in environmental disposal and a requirement to maintain the security of the communication and control system to resist both propagation of software faults and malicious attacks on software from "hackers". These issues, of course, represent factors that may mitigate commercial implementation. However, the gains that are made possible by tribotronic systems in terms of improvements in operational effectiveness, environmental management, and long-term cost control are significant. Critically, tribotronics offers an otherwise inaccessible chance for engineers to introduce a transformational change to machine elements, which provides a pathway for addressing climate change by reducing global energy consumption and material use through wear reduction.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Ian Sherrington is Director of the Jost Institute for Tribotechnology and Professor of Tribotechnology at the University of Central Lancashire, UK. He is also an Affiliate Professor of Tribotronics at the KTH Royal Institute for Technology in Stockholm, Sweden. He is also the current chair of the IMechE Tribology Group Committee, UK, and serves as Executive Director for the International Tribology Council (ITC). Prof. Sherrington's current research activities are centered on the ground-breaking topic of "tribotronics", the development of autonomous, and actively controlled tribological components.

Sergei Glavatskih holds a Chair in Machine Elements at the KTH Royal Institute of Technology in Stockholm. He is also a Visiting Professor at Ghent University, Belgium, and a Visiting Professorial Fellow at the School of Chemistry, University of New South Wales, Sydney, Australia. At KTH, he led research on mechanochemical systems, machine design, and tribotronics. This research is focused on the development of more sustainable, environmentally adapted, and energy efficient components and systems, such as rolling and sliding bearings, gears, wet clutches, seals, threaded fasteners, and lubricants, including oils, greases, and ionic fluids.