Structural Integration of Smart Sensors for the Industrial Internet of Things

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Abstract

Condition monitoring of machine components is an important prerequisite for the implementation of predictive maintenance and other IIoT applications in mechanical engineering. The closer a sensor system can be installed to the location and metric to be measured, the more accurate, less noisy and with lower latency the results will be. Methods and technologies for structural integration are core competences for this purpose. This work briefly summarizes challenges and tools for the structural integration of smart sensor systems. Furthermore, the state of the art of selected commercial products is presented. In this paper the focus is on an IIoT toolbox and its application in the development of a smart ball screw. The proposed sensor system can be easily installed as a retrofit kit in new double-nut ball screws as well as in revised ones.

1 Introduction

Internet of Things (IoT) technologies are increasingly applied in industrial environments. Connectivity at the shop floor level enables data-driven optimization of production quality, maintenance schedules or efficient use of resources. Since microsystems have become ever smaller and cheaper due to miniaturization progresses in microelectronics they provide more computing power at same/less power consumption. Thus, connectivity can be shifted from the machine, i.e. edge level, towards the component level. For instance, MEMS based sensors, that are replacing discrete sensor designs, can be integrated into structural parts of tooling machines.

But also signal processing and analysis can be integrated directly into the sensor system, leading to advanced concepts of smart sensing or extreme edge computing. While increasing the complexity of the sensor system, there are advantages with regard to an industrial application: Shifting signal analysis from the cloud to the edge or directly to the sensor minimizes latency, which is needed for an integration into a dynamic closed loop control system of a machine. Further advantages are the reduction of transmitted data, e.g. for highly dynamic vibration and ultrasonic sensors, and the possibility to implement self-monitoring functions especially for sensors in critical control loops.

In this paper, challenges in structural integration of electronics in machine tool parts are discussed, an IIoT smart sensor toolbox is proposed, options for miniaturization of such systems are highlighted, and a selective overview of already available IIoT condition monitoring systems is given.

Finally, the integration of a smart sensor system into a ball screw of a tooling machine is presented. Taking measurement data directly at this component offers the options to monitor the static preload force and temperature, that influence the production quality of the process and give indication of component wear out. Since the ball screw is a moving part of the tooling machine, wireless connectivity and wireless power supply are considered as preferable feature and thus, had to be realized. Several basic designs of the integrated sensor electronics have been considered; prototypes were manufactured. Characteristics of the different designs are discussed with the goal to alleviate finding an optimal solution for a structural sensor integration use case.

2 Structural integration challenges

2.1 Main challenges

Structural integration of electronic components like sensors and microcontrollers in typically metallic environments is a challenging undertaking because of the interdisciplinary complexity and restrictions of component design and performance. Deep understanding in mechanical engineering, simulation and their applications is essential for the successful realization. Moreover, capabilities and competencies in micro- and nanoelectronics are central fields of importance such as handling of 3D-integration technologies, wireless data communication technologies, electromagnetic compatibility (EMC) issues and the awareness of energy aware design of electronics. Requirements and findings out of both engineering fields have to be combined in a way that the structural properties (e.g. size, stiffness, dynamic behaviour) of the original component is not deviated by structural integration of sensors.

2.2 IIoT smart sensor integration toolbox

2.2.1 Basic IIoT toolbox elements

Structural integration is a generic approach, which is applicable for different smart sensing solutions. Due to its significant potential and relevance for future technology trends a special development for a singular application case is not a preferable solution. Instead, the development of a generic IIOT toolbox allows a continuous learning of technological challenges from different applications. However, a smart sensor for IIoT basic functionalities comprise the integration of

- calibrated reliable sensors (e.g. sensors for temperature, force, vibration, ambient data acquisition)
- data [pre-]processing and data storage capabilities for enablement of smartness features
- wireless, wired or integrated (e.g. by battery) energy supply and management
- wireless or wired data transmission connecting the IIoT device to the edge, computing cloud and/or the machine and related protocols /interfaces like Open Platform Communications Unified Architecture (OPC UA).

In the following selected technological options and requirements are discussed.

2.2.2 Related sensor technologies and requirements

Sensors are the window to the outside world of smart components. They collect data for the decisions and actions made by the system. Sensors convert physical or chemical input into machine-readable electrical signals. They are essential components of the IIoT. Temperature, force and acceleration are of particular importance to describe the condition of a mechanical component or machine element. In addition, process parameters (position, angle of rotation or speed) and environmental conditions are of common interest.

Integrating sensor systems into mechanical components and machine elements results in requirements for:

- Miniaturization: To precisely measure properties at the point of origin, integration into the smallest components is often necessary. Highly miniaturized and customized sensor systems open new application possibilities.
- Service life: The sensor system must not reduce the service life of the original machine element.
- Robustness: Must be appropriate to the original machine element and must not limit its service life or field of use.
- Maintenance: Must be reasonable. The sensor system must not lead to an increase in maintenance e.g. recalibration or frequently battery replacement.
- Cost: Must be reasonable compared to the original machine element, the value added and the use case e.g. cost savings by predictive maintenance.

Sensors consist of a sensing element, a measuring electronics and a signal output. A smart sensor additionally contains advanced signal and data processing electronics. The technology of the sensing element depends on the measurement task. It can be individually fitted to the application. The measuring electronics is optimized for the sensing element and the measuring principle and outputs a machine-readable analogue or digital signal. The signal output is either wired or wireless. Smart sensors include extensive signal and data processing through to the calculation of statistical parameters, trends and recommendations for action, e.g. for maintenance work or the replacement of the component.

Sensors are offered in different stages of development. There is a large selection on the market for direct installation on machines and systems. The integration of sensor systems in components and machine elements, on the other hand, cannot be achieved with commercial off-the-shelf (COTS) systems. A sensor system adapted to the application is required. This in turn can use COTS sensors and electronic components. An even greater specialization is possible with individually designed sensor components.

2.2.3 Options for wireless data communication

Since many industrial IoT systems comprise moving parts, wireless connectivity is preferable. Wireless modules are highly efficient, flexible, easy to install and need rarely maintenance. Unfortunately, there is not a single radio technology available that meets all requirements which are significantly different depending on the specific application [1]. Especially data rate, energy efficiency, range and reliability must be partially weighted against each other. For structure integration of smart sensors restrictions in size (miniaturization) and availability of energy play a significant role. In Table 1 a brief overview and raw classification of existing and known wireless technologies is given as a guideline.

Of course, also additional aspects have to be considered for a final technology selection such as costs, standardization, compatibility with industrial systems, real-time capabilities (closed-loop control), reliability and security which are not the focus of the discussed research activities, here.

In the present work Bluetooth and RFID were selected as wireless technologies for prototype development: Bluetooth has its advantages in energy efficiency, size, easy system integration, and handling. RFID is almost unbeatable when energy efficiency is the top priority. Radio waves emitted by the reader are used as exclusive power supply but with limitations due to very low data rate and short range data communication. However, another evolving appropriate wireless technology for structure-integrated smart sensors is mioty® [2]. mioty® is a low-power wide-area network (LPWAN) protocol, optimized for long range (~10km), low power consumption and robust and reliable transmission. The data rate per sensor node is very low but a very large number of nodes can be handled simultaneously without loss.

Table 1: Comparison of current wireless communication technologies for IoT applications.

	Energy efficiency	Range	Data rate	Size	System Integration and handling	Robustness (interferers and difficult radio conditions)	Latency
Bluetooth®	High	Medium	Medium	Small to Medium	Easy	Medium	depends on current band utilization; no guaranteed latency
ZigBee®	High	Medium	Low	Small to Medium	Specific Gateway	Medium	Not rated for low latency
WLAN	Low	Medium	High	Medium	Easy	Medium	depends on current band utilization; no guaranteed latency
4G / LTE	Low	High	High	Medium	Medium	Good	Depends on cell utilization
mioty® (LPWAN)	High	High	Very Low	Medium	Specify Gateway	Very good	Very high latency
RFID	Very High	Low	Very Low	Very Small	Specific RFID Reader	Very good	High latency

2.2.4 Energy supply, transmission and management

In the subject of wireless sensor technology, various approaches to supply energy can be realized in a variety of ways. But such sensor based systems require a reliable and finally stable energy source. The choice of the appropriate method depends on the specific requirements of the system and requires careful consideration of the advantages and disadvantages of different technologies. Potential options include power harvesting from the ambient e.g. using solar cells, battery operation with potential energy budget limitations or technical ability to change batteries, and the use of wired power sources. However, within the context of structural integration of electronics in highly dynamic machine components, these conventional approaches partially turn out to be inadequate. Regular battery changes prove impractical while power harvesting might fail due to limited and often unreliable power generation. Battery supplied systems are limited in computing power, data rates, communication technology due to the limited initially provided amount of stored energy and device lifetime. Implementing a wired power supply or a drag chain also encounters challenges. These would introduce additional inertia as well as complex mechanical structures. Therefore, an alternative solution was developed that enables wireless power transmission without relying on cables. This innovation is based on coil-based inductive transmission principles (for details see chapter 4).

2.2.5 Options for integration of data analysis

The generic features of a smart sensor can be summarized by integrated analog-to-digital-conversion, bi-directional communication (see above), and digital signal processing. The integrated functions range from compensation of noise and temperature influences, over auto-calibration to complex calculations [3]. A highly efficient information extraction from the acquired sensor signals is desirable, since less data has to be transmitted from the smart sensor. However, this requires algorithms like calculation of indicators or classification of signals.

For special applications like condition monitoring of rotating equipment, fully integrated smart sensors are commercially available [4], their compact package makes mechanical integration straightforward, but usually data analytics capabilities are restricted and lack flexibility. For inertial measurements and inclinometers, even machine learning functions have been integrated into packages [5].

Still, a design with discrete MEMS sensing and processing units is attractive due to the greater customizability for individual solutions like on-line learning. While training a full neural network seems still not feasible on a small microcontroller, adjusting certain weights has been demonstrated [6]. This also allows combining different sensing and microcontroller units for an optimized system design.

2.3 Miniaturization as a key enabler for structural integration of electronics

Typically, the development of IIoT electronics is a step-by-step approach as shown in Fig. 1. Based on conventional organic FR4 printed circuit boards (PCBs) electronic circuits are fabricated with soldered standard surface-mounted devices (SMD). The assembly can be performed on front and back side on multi-layer PCB substrates to increase the device density. PCBs are available in rigid, flexible and rigid-flex substrate material types, but all with limited size scaling and device bending properties for structural integration.

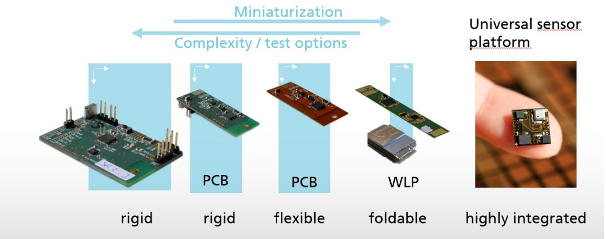

Figure 1: Approaches in the development and realization of IIoT smart sensor electronics.

2.3.1 Options in miniaturization of electronics using advanced packaging technologies

Further miniaturization means scaling down wiring and interconnect features to maximize the I/O density using advanced silicon mass production technologies [7]. The established baseline substrate is standard PCB which is reliable but needs large interconnects (solder balls) between FR4-material (PCB) and silicon (functional flip-chip (FC)-dies) for stress compensation. PCB ball sizes down to 100 µm are usual and ball sizes down to 30 µm are possible (but with more effort and a higher yield risk). A satisfactory solution for miniaturization is the 2.5D-interposer. Instead of PCB the substrate is a silicon die with wiring on top & bottom side including a through silicon vias (TSV) for a high-density electrical connection of top & bottom side. Since the FC-bonded dies and the functional circuits are both silicon based there is no general mismatch in the coefficient of thermal expansion (CTE) due to temperature changes during fabrication or usage. This allows smaller interconnects with smaller pitch resulting in a smaller pitch and much higher I/O density.

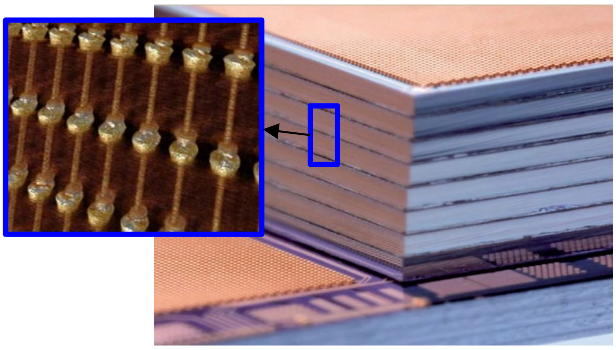

Figure 2: 3D-stacking of FC-dies with TSVs, top & bottom metallization as shown in the x-ray tomography on left side.

Production of high I/O density levels is realized on wafer level (up to 12 inch). This allows patterning with lithography with mask exposing by stepper or mask aligner. A mask aligner allows even one very large single die or substrate on 12 inch wafer. Achieved solder bumps dimensions are from around 20 µm bump height & diameter down to 3 µm diameter and ~4 µm height. The advantage of Si-interposer compared to PCBs are smaller distances between I/Os and less wiring metal (due to smaller solder bump diameter than the solder ball diameter used for PCBs). This is reducing signal latency time, reducing the electrical power consumption, and increasing the bandwidth.

Further miniaturization progress can be achieved utilizing “3D-stacking” and “direct bond” technologies for even enhanced I/O density, higher data bandwidth and higher package reliability on the one hand and also increased fabrication complexity on the other. For 3D-stacking the 2.5D-interposer is expanded by additional assembly of FC devices-on top of the 2.5D-interposer stack (see Fig. 2) with theoretically no limits for additional tier levels. For this approach additional TSVs inside the FC-dies are needed in order to establish the vertical power/signal routing.

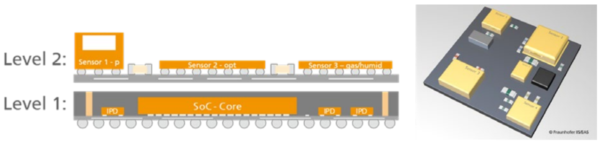

Figure 3: 3D SiP architecture of the universal sensor platform. Level 1 comprises a multi-core RISC-V SoC fabricated in 22 nm FDSOI technology and related passive devices (left). Level 2 can be equipped with a variety of sensor devices (left: cross-section, right: top view).

A special sensor node for IIoT condition monitoring applications utilizing such advanced packaging technologies was demonstrated in a cooperation of several Fraunhofer institutes called “universal sensor platform” (USeP) [8] (see Fig. 1 and 3). This micro edge computing device is fabricated in a 3D-System-in-Package (SiP) architecture merging sensing capabilities in variable configuration with significant computing power enabling artificial intelligence functionalities in a single IIoT node. On top level SMD MEMS devices for initial measurements (acceleration, gyroscope, vibration) can be implemented as well as sensors for gas and ambient condition data capture (humidity, temperature, volatile organic compounds), for instance. Hardware based security features are also already implemented in the SoC core.

As shown wafer level packaging (WLP) technologies are beneficial for the realization of systems in minimal size in mass production with high reliability but are mainly restricted to processing of e.g. microcontroller as silicon bare die components which are typically not available for small series prototyping production. Very limited are also the solutions for integration of passive components (L, C, R) on wafer level. Typically power management, wireless data communication and external peripheries have to be included and realized finally on PCB to build up a full IIoT sensor node counteracting the miniaturization efforts of advanced packaging.

Thus, a desirable packing technology solution should combine standard assembly processing advantages with a partially flexible high I/O density substrates. Here, this is realized in a rigid-flex Si interposer technology where a flexible wiring bridge connects the rigid parts equipped with standard SMD components (see Fig. 4). For instance, in this way a need for extreme curvature designs for embedded systems with high I/O densities can be satisfied by using standard wafer processing technologies. Therefore, effort/pricing is reasonable for application, customer, and market. This approach is highly beneficial for structure integration of electronics due to its flexibility in shape to fill out curved columns or square shaped spaces in metallic components.

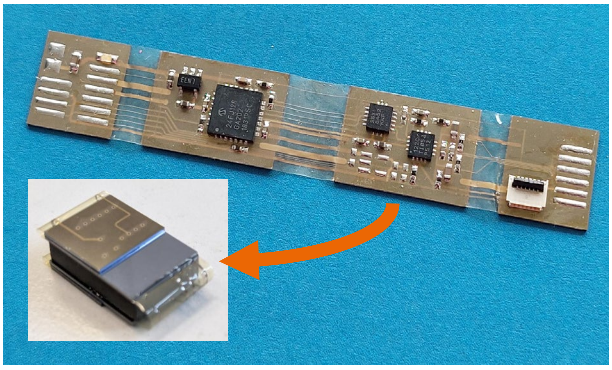

Figure 4: Example of rigid-flex silicon interposer - capable for adaption on surface curvature or even foldable to a die stack.

3 Available IIoT solutions

The IIoT concept is based on interconnection of assets and production goods as well as sensors and actuators. It enables comprehensive exchange, analysis and collection of data in near real-time. Information is made available in central locations. Thus, patterns and trends of technical and administrative processes can be identified more easily. This can lead to an increase in productivity and efficiency or generate other economic benefits. Interconnected smart sensors can support the automation of condition monitoring. Continuous and in-depth monitoring of assets and processes becomes possible. Thus, condition monitoring is important to realize predictive maintenance services. Condition monitoring is currently mainly carried out manually based on empirical knowledge or mobile measuring devices. Automated condition monitoring needs machine elements, components and systems equipped with interconnected sensors. Various manufacturers offer individual products for this purpose; some solutions are discussed in the following.

A sensor system for monitoring rotating machines is presented in ref. [9]. It records vibration and temperature data of the corresponding aggregates. A wireless mesh network connects multiple sensor units and a cloud gateway. A digital service evaluates the data of all sensor units and provides an error analysis. A system for the condition monitoring of motors and rotating components of powertrains is published in ref. [10]. The sensor system provides information on vibration and temperature. It can also warn of overload situations. A cloud service processes the data and calculates maintenance information. A condition monitoring toolkit is described by ref. [11]. It is a holistic solution for monitoring machines, systems and processes. Sensors with an IO-Link interface can be used, e.g. temperature, vibration and pressure. The sensor data is collected and evaluated in the base unit of the sensor system. The system works independently of a cloud, but the data can be accessed via a network connection. These three references describe a number of benefits for condition monitoring e.g. increase of availability, reduction of maintenance costs, preventing unplanned downtime, optimizing processes, improving quality and planning security. A simple retrofitting of the sensor systems to the machine components is furthermore described as an advantage. With this method, no structural changes to the machine components are required.

In contrast, the following examples integrate sensors and data processing units directly into the structure of machine elements. This results in both technically and economically useful measurement data. Ref. [12] describes a sensor system for monitoring tool wear and in-process control in machining. It measures the cutting forces directly on the tool. The sensor system monitors the forces for each individual blade of the cutting tool. AI algorithms are used for data evaluation. In ref. [13] a condition monitoring system based on smart screws is presented for various assets and applications. Sensors are integrated on screws and bolts to measure static and dynamic loads as well as temperatures. The integration technology does not change their mechanical properties. An edge computing unit processes and analyzes the sensor data close to the sensors. Ref. [14] describes a sensor system for monitoring the condition of bearings in industrial machines e.g. motors or blowers. Sensors, power generation unit and wireless device are integrated into the bearing. Temperature, vibration and speed can be measured and transmitted to the outside. The dimensions and load capacity of the bearing are not changed by the sensor system. The three references describe various advantages over non-structure-integrated condition monitoring systems. This includes improved sensitivity, earlier detection of deviations, measurement in the flow of force and access to parameters that are not measurable from the outside. In addition, these systems have all the benefits of the condition monitoring systems described above [9-11].

Another important and very frequently used machine element is the ball screw. Several companies already offer sensor systems for condition monitoring. Ref. [15] describes a sensor system for measuring temperature and mechanical vibrations of ball screws with sensors on the flange of the nut. Four vibration parameters (frequency, acceleration, speed and displacement) are determined from the total vibrations. Temperature trends are identified through long-term monitoring and data analysis. The sensor system presented in ref. [16] monitors the loads on the ball track directly at the rolling contact. It aims to continuously monitor the preload of the nut on the spindle shaft. In ref. [17] Temperature and vibration combined in a multi-sensor system are used to gather data for predictive maintenance. An edge computing module is used for calculations, historic log and data analysis. The sensor system described in ref. [18] also combines sensors for monitoring vibration and temperature. Sensor data are processed by an edge computing system. In ref. [19] a completely different technology for condition monitoring of ball screws is presented. This sensor system consists of a camera with a lighting unit. These are attached to the nut of the ball screw. The camera continuously takes pictures of the spindle at each section. The image data is evaluated with AI algorithms in a data processing unit. The latter five systems [15 to 19] monitor the condition of ball screws using different methods. The most cited benefits of condition monitoring are the detection of abnormal operating behaviour, indication of overload, determination and quantification of wear, prediction of trends and future behaviour, optimization of the maintenance plan and reduction of maintenance costs.

Sensors for vibration and temperature are most frequently used for condition monitoring but a direct measurement of the preload in the flow of force of the ball screw is currently not considered in available products. Thus, the condition monitoring system proposed by the authors in the following chapter could fill a technological gap in the future with relevant progress for an improved accuracy for failure detection, remaining useful life prognosis and process optimization capabilities.

4 A smart ball screw condition monitoring system

Digitalization, Industry 4.0 and IIoT technologies are driven by the continuous need to reduce the total cost of ownership (TCO) and overall equipment effectiveness (OEE). Thus, the investment in smart components and their development must pay off in a reasonable period of time and the technology must be easy to apply with low additional maintenance efforts. From this point of view machine tool parts are very interesting for structural integration of sensors for condition monitoring due to indirect interaction with the process due to their location in vicinity to the machining process closest to the place of action inside the machine tool. Especially ball screws face typically a high workload and wear-out which results in regular maintenance efforts for replacement of these parts. Thus, an extension of usage time would be very beneficial with predictive maintenance capabilities to optimize the equipment effectiveness. Typically, ball screws are replaced after given number of working cycles given in the data sheet by the supplier without consideration of the actual state of wear and working condition forecast. Additionally, due to the strong mechanical connection and coupling to the machining process a smart ball screw condition monitoring system is an enabling technology for the optimization of the production process itself [20]. Thus, the ball screw was selected as an application example to investigate and demonstrate the potential of structural integration of electronics in machine tool parts.

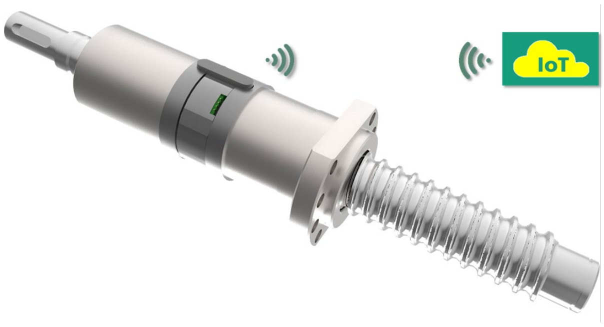

Figure 5: IIoT enablement of a ball screw by structural integration of a smart sensor system.

4.1 Smart sensor ring concept for structural integration of electronics

Condition monitoring of machine elements, and more specifically of ball screws, has many benefits (see section 3). A sensor system for double-nut ball screws is described in the following as shown in Fig. 5. It is designed in the form of a metallic sensor ring and fits exactly between the two nuts made from the same material. The sensor system therefore is in the flow of force and measures the static preload and dynamic forces during the machining process very precisely and with high time resolution. The sensor ring also contains a temperature sensor and can be optionally equipped with additional sensors for e.g. acceleration and vibration measurements. With this approach, the factory fitting of new ball screws is just as possible as the simple retrofitting of systems already in use. The measured data is transmitted wirelessly to a gateway and can be evaluated both on-the-edge and in the cloud. The gateway can also be connected directly to the machine control. The sensor ring is supplied with energy wirelessly and inductively. The energy can be supplied over the entire movement range, as well as at defined positions e.g. for changing tools.

The core electronic components are implemented on rigid PCBs, designed for maximum space efficiency through a high-density packaging scheme. A flexible wiring carrier allows a functional bending radius spanning the gaps between the individual rigid modules to enable the electronics and energy storage devices to optimally fill the ring's available space. This approach is easy to manufacture and enables fast integration as well as the replacement of individual modules rather than the entire electronics system. This also facilitates the updating of specific modules further along the product's lifespan, making it environmentally friendly.

4.1.1 Wireless data communication

The smart sensor ring was fabricated in different versions using Bluetooth and radio-frequency identification (RFID) technologies (see Fig. 6) to demonstrate the flexibility of the designed IIoT toolbox with respect to the applied data communication technology and the intended use as discussed in chapter 2.2.

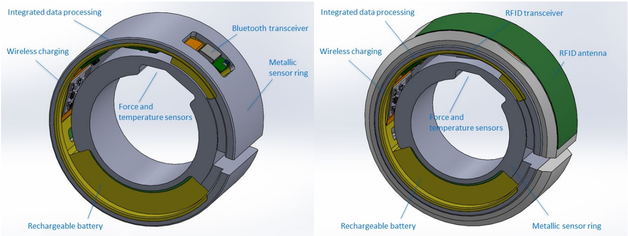

Figure 6: 3D model of smart sensor ring with Bluetooth (left) and RFID (right) communication interfaces.

Both smart sensor rings basically contain the same sensors (temperature and force), same wireless energy supply as well as power management electronics. Both sensor signals are read out by a measuring electronics, then pre-processed and finally transmitted to a gateway via the communication interface. Here, the Bluetooth Low Energy (BLE) module is placed on a flexible printed circuit board to provide continuous measurement data communication with medium data rate. The antenna is (typically) an integral part of the module. BLE enables easy system integration supported by a very compact design and the typically available extensive software stack. The energy efficiency is high, but not as high as of RFID technologies. In addition, BLE enables secure communication, e.g. encrypted with AES128. The range (approx. 10 to 50 m) is scalable, on the one hand via the module selection and on the other hand via a configurable transmission power. This is of course accompanied by a corresponding power requirement.

In order to facilitate communication between the RFID sensor ring and the RFID reader, the use of a flexible antenna connected to the RFID transponder is necessary. A thorough examination of various antenna designs has revealed that a meandering dipole antenna with a distance of only 5 mm to the metal surface can provide sufficient transmission and reception characteristics of up to 5 meters. The design of the antenna poles in a curved fashion serves to minimize the extension on the longitudinal side, therefore reducing the space requirement on the sensor ring, while providing the necessary transmission and reception characteristics for effective communication between the RFID sensor ring and the RFID reader. This newly developed and specially adapted RFID antenna is connected to the sensor ring as a communication module.

The RFID transponder is mounted directly on the flexible antenna to prioritize the optimization of transmission and reception characteristics. The communication between the RFID transponder and the external RFID reader is passive and battery-independent, thereby ensuring that it is always possible to query the identification number of the RFID transponder and its location within the RFID field, even with an empty battery. This further enhances the reliability and functionality of the system.

The system's ability to integrate the analogue front end directly to the RFID data logger through an I2C bus ensures a reliable and efficient means of delivering data regarding the wear and lifetime development of the ball screw. The system's capacity to read various sensor values directly inside the ball screw provides valuable insights into the condition of the mechanical tool, thereby enabling effective condition monitoring. The feature is particularly useful in preventing potential damage resulting from overheating, which can significantly reduce the lifespan of the entire system or attached tool. Experimental results have confirmed that the systems improved software routines have led to a substantial improvement in the stability of the RFID communication. Specifically, the system exhibits a higher degree of resilience in terms of connection disruptions and is able to automatically resume data exchange once the connection is restored. This feature effectively minimizes the potential for data loss and downtime, thereby promoting more efficient operation of the system.

It is worth noting, however, that RFID communication can transmit fewer data in the same amount of time compared to its Bluetooth counterpart. Nevertheless, RFID offers a significant advantage over Bluetooth in terms of wireless communication. Specifically, the power consumption of the RFID data logger is substantially lower than its Bluetooth equivalent. This is particularly relevant in situations where constant power supply is not readily available. In such scenarios, the lower energy consumption of the RFID system makes it a more practical and efficient option.

In the case of a constant power supply provided through the use of multiple charging zones, a significantly higher energy budget is possible, enabling the system to capture more data. This feature is particularly relevant in condition monitoring applications, where the system must capture a large amount of data to accurately monitor the condition of the equipment. Thus, the Bluetooth version is capable of further enhancing the system's abilities by logging and sending more data in the same period of time.

4.1.2 Wireless energy supply and power management

The energy supply for the sensor systems was ensured via a wireless energy supply through inductive, resonant energy transmission which enables a reliable and efficient energy supply even over an air gap of several millimeters. To ensure a uniform energy supply over the entire radius of action, several transmitting coils were integrated into the design. To guarantee the energy supply in case of possible disturbances, an accumulator was implemented on the sensor side to buffer the supply voltage. The inductive energy transmission provides a power of slightly more than one watt. This power significantly exceeds the requirements of the sensor components.

The power module of the smart ball screw is supplied with voltage via a rectifier network. The power module is also responsible for providing the system's internal voltage domains, charging the buffer storage, and protecting the battery from various fault scenarios. Many possible sizes and types of energy storage were considered to find the optimal solution for the specific application. The use of modular components and customizable parts also allows for the type of storage to be changed and adapted to meet the required conditions.

4.2 Machine integration

Prototypes of the sensor system were manufactured and installed in a machine tool environment a Deckel-MAHO CNC milling machine. The feed motion of the X-, Y- and Z-axes is derived from the drive and transmitted to the slides by individual ball screws. Taking measurements directly at the ball screw at Y-feed with the sensor system offers the option to monitor continuously static and dynamic preload forces and temperature. The setup also includes a data logger for external data acquisition, data processing and communication.

5 Summary

Condition monitoring of assets and machine components in industrial fabrication has many advantages. The most important are: increasing availability, reducing maintenance costs, preventing unplanned downtime, optimizing processes, improving quality and planning security. More comprehensive condition monitoring is enabled by the latest technological advances in sensor capabilities, information technology and data processing. In recent years, this development has led to increases in performance, miniaturization and cost reductions in the required sensor systems. Research and development projects are working on seamless condition monitoring solutions right down to the individual machine element. An important and frequently used component is the ball screw. The main benefits of ball screw condition monitoring are: detection of abnormal operating behaviour, indication of overload, determination and quantification of wear, prediction of trends and future behaviour, optimization of the maintenance plan and reduction of maintenance costs.

The basic components of a condition monitoring system are sensors, data processing unit, communication interface and power supply. Many of these components are already available as COTS. The situation is different when sensor systems need to be integrated into the structure of machine elements. Then individual solutions are required that are precisely adapted to the respective application through miniaturization, energy efficiency and a competitive price. An efficient development approach could be enabled by the proposed IIoT toolbox for structural integration.

As an application demonstrator for this toolbox a smart ball screw was developed. It contains a sensor ring for monitoring of temperature, preload force and optionally vibration and other parameters. The sensor data is pre-processed in the sensor ring and wirelessly transmitted to a gateway at the outside. The energy supply is also carried out wirelessly. The data can be transmitted from the gateway to a machine controller or a cloud. In addition, the data can be analysed on-the-edge. The proposed sensor system for ball screw condition monitoring goes beyond the state of the art of commercially available products. It measures temperature and pre-load directly in the flow of forces and integrates data processing, communication interface and power management seamlessly into the mechanical structure of the sensor ring and hence the ball screw assembly.

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